COMPUTER-AIDED DESIGN OF POWER SYSTEMS

USING ENERGY STORAGE

By

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CHAPTER I

INTRODUCTION

The peoples of the world are increasing their use of controlled
power at terrific rates. In the United States the consumption of elec-
trical power alone has almost doubled every ten years since 1900 (1).
New natural reserves of stored energy are continually being discovered
but reason indicates that all such sources must eventually be depleted.
It is also possible that at some point the chemical use of fossil fuels
would become so important that they would be reserved for uses other
than electrical or mechanical power generation. Therefore, it is im-
portant that other sources of stored energy be investigated (2).

The conventional sources of energy are the fossil fuels and hydro-
electric energy. Atomic energy is beginning to enter the picture,
also. In these energy sources, the first step, that of storing the
energy in some form, has been taken by nature. Man has taken this
stored energy and used it to perform useful work. In some instances
the fuel could be used directly; natural gas and coal are examples of
this. In other cases, such as crude oil, some sort of processing is
required before utilization.

Figure 1 is a block diagram representation of the stages through
which energy passes from source to use. In this figure the storage of
the energy acts as a buffering device for the energy source to supply
energy for use uncorrelated in time. Consider the problem that arises

1

ACCOMPLISHED BY NATURE
IN MANY CASES

ACCOMPLISHED BY MAN

```
┌─────────────┐     ┌─────────────┐     ┌─────────────┐     ┌─────────────┐
│   USEFUL    │     │             │     │  PROCESSING │     │   ENERGY    │
│   ENERGY    │ ──▶ │   STORAGE   │ ──▶ │  (IF NEEDED)│ ──▶ │    USE      │
│   SOURCE    │     │             │     │             │     │             │
└─────────────┘     └─────────────┘     └─────────────┘     └─────────────┘
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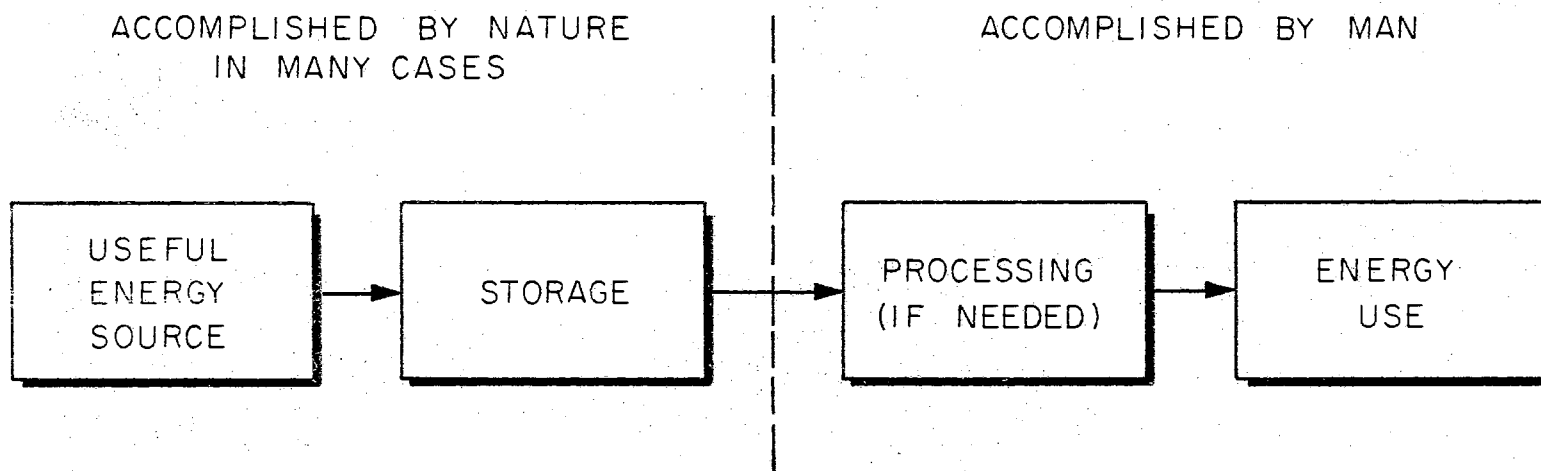
Figure 1. Block Diagram of the Stages in the Utilization of Energy for Useful Purposes

for the utilization of unconventional energy sources such as winds, sunlight, and tides. The energy is available but not necessarily at the same time that it is needed for normal purposes. This gives rise to a number of questions. Can this energy be harnessed effectively? It has already been shown that it can be harnessed. What direction should research efforts take for more effective utilization? Should the researcher attempt to find uses for this energy whenever it is available, i.e. some time-independent application such as the refining of copper at the mine? Or, should he attempt to pattern his efforts along the line of the natural process and store the energy until needed? Certainly efforts should be and have been exerted in both directions. This particular research effort is directed along the latter path since inevitably the major requirements must be met upon demand. After consideration of the general area of unconventional energy sources, Oklahoma State University has focused effort on extracting energy from winds and sunlight (3). The buffering device used to match the supply to the demand is chemical in nature; it is an electrolysis cell - gas storage - fuel cell system (1).

In a research proposal to the Rockefeller Foundation, McCollom (4) has set forth the needs of a developing country for small, independent power sources as a first step in a nation's efforts to emerge from the poverty associated with manual farming techniques. Ethiopia was chosen as a possible test site because of the promising conditions there. The climate and the soil are conducive to increased productivity from irrigation. Crops grow well during the wet season but irrigation is not practiced during the dry season. Small power sources could well be used here.

Beyond this basic application of power McCollom (5) envisions a step-by-step evolution of the society as power is used not only to irrigate the crops but also to aid in the establishing of a processing plant for those crops. Then the nation can establish light industry and begin to develop conventional power plants and the attendant power transmission grids.

In the United States, Canada, and other more highly developed nations there are remote villages, hunting lodges, and small military stations whose location makes the transmission of electric power quite expensive. It is possible that both fuel and electrical power could be provided more economically to them by an energy storage system than by a conventional system using a long transmission line. In order to utilize the energy available in these unconventional sources, one must design a system which can compete economically with conventional systems at the times and places involved. This fact requires that the composite system be analyzed and optimized as a unit for the job to be performed. Therefore, there is a need for the development of a design procedure to optimize the total system from an economic viewpoint.

This research effort develops the engineering procedures and computer programs necessary for the designing of an economically optimum power system utilizing one or more of the unconventional energy sources, some type of energy storage device, and reconversion to a useful form. The resulting procedures and programs are not limited to power systems but may be applied to any design problem whose nonlinear effects occur in series as long as these nonlinearities can be graphed. The GPSS programs developed are a unique application of a discrete simulation language to a continuous process and are shown to be both logical and

effective. One of the outgrowths of the programs developed for this simulation was a paper presented at a national convention (6). A second unique development in the use of GPSS is the ability to make a simulation, test the result, adjust one of the variables, and then make another simulation within the computer. This sequence may be repeated as often as desired in a single program.

Chapter II presents a review of the literature pertaining both to wind power utilization and to the development of simulation techniques. Wind power was chosen as the unconventional source to be used in the example since it is the one that has been investigated most often. Simulation of the system is necessary because of the lack of correlation between the availability of the energy and the use of the energy. Chapter III presents a working knowledge of the simulation language, GPSS. The basic entities are presented and their method of operation is explained in sufficient detail for the reader to be able to follow the discussions in the succeeding chapters.

Chapter IV presents the design procedure and the computer programs to be used in it. The design procedure is outlined in some detail including the reasoning behind each choice of method where alternatives are available. There are certain preliminary calculations which are simple to make and quite productive in giving lower limits on design variables; these are presented. A discussion of the purpose and use of each of the computer programs is included.

Chapter V contains the application of these design procedures and programs to an example power system. The procedures outlined in Chapter IV are demonstrated by actually carrying to completion the design of a useful power system.

Chapter VI contains conclusions and recommendations regarding the design tool which has been developed as well as some specific suggestions for future developmental work.

CHAPTER II

REVIEW OF LITERATURE

Many different sources of energy may be classed as unconventional.
Among these are wind, sunlight, tides, and geothermal. Of these, wind
and sunlight are fairly well distributed over the earth with the ex-
ception of sunlight in the polar regions. Of these two, wind has been
investigated by a greater number of people and will be the unconven-
tional source used in the example system whose design will be carried
through the text to illustrate the use of each operation.

Wind Power

The work done by Betz (7) in 1927 initiated investigations into
the efficient utilization of wind power. It was concluded by most
investigators that wind power was not economical because of the vary-
ing velocity of the wind. Putnam (8) in the early 1940's attempted to
overcome this weakness by mounting a large wind generator in an area of
constantly high velocity wind in a mountainous region of Vermont but
failed because he still could not compete economically with convention-
al power systems in that location. Golding (9) met with the same eco-
nomic failure in England in the 1950's. In August of 1961 the United
Nations sponsored the Conference on New Sources of Energy (2). This
conference in Rome reported not only on the current wind energy studies
but also on the current investigations of solar energy and geothermal

energy.

In 1963, obtaining energy from unconventional sources was focused upon by the engineering faculty of Oklahoma State University. Local power companies became interested through a conference and a report written by some of the engineering staff members (1, 3). Research sponsored by the power companies in the area of energy storage has continued since that time (10, 11, 12, 13). Ramakumar (11) is currently investigating the development of a rechargeable fuel cell which would act as an input/output device for the storing of energy in the form of hydrogen and oxygen. Gibson (13) has made a study of the energy available in wind and presents a simulation technique which may be used in further study of wind energy systesm. He also states that reevaluation of several of these unconventional sources is desirable due to anticipated future needs and improved energy storage techniques such as are resulting from Ramakumar's work.

<div align="center">Simulation – A Design Tool</div>

Design by simulation is not a new idea. M. I. T.'s network analyzer was an economic asset to many power companies during the infancy of power systems in the United States. The United States Navy has simulated various shipboard situations for many years in the design of their crafts. The aircraft industry has found it profitable to install complex simulation equipment for help in designing their airplane structures. The current status of the art of simulation is reflected in this editorial comment in the February 1968 edition of Simulation (14), "Every few days this editor gets a telephone call from someone in desperate need of a person with simulation experience to come work for

them." Because of the importance of simulation in industry today and its use in this study, a brief review of the literature on this subject is in order.

In Volume 1, Number 1 of <u>Simulation</u>, a publication of Simulation Councils, Inc., McLeod (15) defines simulation as "the act of representing some aspect of the real world by numbers or symbols which may be easily manipulated to facilitate their study." This general definition of simulation leads to the investigation of several aspects of the practice of simulating, or modeling physical systems. The last part of the definition "...which may be easily manipulated..." provides a clue as to the reason for the use of simulation, namely, it is easier and more economical to build and/or alter a model than it is to perform the same operation on the actual system. In another article in the same publication, Mr. McLeod (16) gives some reasons for simulating a manned spacecraft. They are:

1. A manned spacecraft cannot be test-flown on the moon as a normal aircraft can be flown here on earth.

2. Once the spacecraft is launched, a man's life is committed to the successful operation of many more complex systems over which he has less control than in the case of an aircraft, and

3. The dollar cost alone prohibits extensive flight testing.

These three reasons represent the major reasons for using simulation, i.e. less cost, easier, and, in some cases, less danger to human life.

Analog Simulation

Two systems are said to be analogs if there is a one-to-one correspondence between pertinent elements of the respective systems as

well as their excitations and their responses. In his book on analog

computation, Jackson (17) presents a history of analog devices. It is

summarized here:

1. Graphic solutions of surveying problems was probably the

   first analog computation.

2. The slide rule, developed about 1600, was probably the first

   analog computer.

3. The next noteworthy analog device was the nomogram. The idea

   was introduced by Descartes, improved by Margetts and finally

   named by D'Ocagne.

4. The planimeter was developed about 1814 by J. H. Herman and

   was improved about 1854 by Jakob Amsler who devised the polar

   planimeter.

5. An outgrowth of the polar planimeter was the ball-and-disk

   integrator which was invented by James Thomson.

6. In 1876 Lord Kelvin used the ball-and-disk integrator to build

   a harmonic analyzer which was used to predict the height of

   tides.

7. The integraph, an integrating device similar to a ball-and-

   disk integrator, was invented independently by Abdank

   Abakanoviez in 1878 and C. V. Boys in 1882.

8. Vannevar Bush started work in 1927 at M. I. T. on the first

   differential analyzer. The resulting machines are cumbersome

   but still quite useful for some applications.

9. During World War II the development of the operational ampli-

   fier made possible the construction of a general purpose ana-

   log computer in 1947 that was quite accurate. Since then the

size of these machines has grown from 20 amplifiers to 500 or
1000 amplifiers.

Fifer (18) lists these historical developments and adds the chop-
per-stabilized d-c amplifier which is primarily credited to E. Goldberg
of the RCA Laboratories.

Present-day electronic analog computers consist not only of a
collection of high-gain amplifiers but also of a variety of peripheral
equipment such as potentiometers, diodes, multipliers, function gener-
ators, relays, meters, and recorders. The literature reflects the con-
tinued interest in improving the electronic analog computing equipment
(19).

An electronic analog computer is very versatile in its applica-
tions. Karplus (20) shows that it is particularly well suited for
solving problems involving electromagnetic fields. Fifer (18) lists a
significant cross-section of applications. Some of them are design of
aircraft structures, missile control and guidance systems, fire con-
trol systems, propulsion systems, thermodynamic and heat transfer
problems, electron optics, nuclear reactors, fluid kinetics, valve and
shock mount design, and chemical and petroleum plant synthesis.

The method of using an electronic analog computer in a simulation
is set forth in many texts (21, 22, 23). Linear transfer functions
(Laplace transformable) are simulated by combinations of summing ampli-
fiers and integrators. Nonlinear transfer functions must be simulated
by some rather complex peripheral equipment. The most common of these
function generators requires tedious adjustment of a number of poten-
tiometers. These potentiometers adjust break points and slopes to give
a straight-line-segment approximation to the desired transfer function.

When a given excitation or combination of excitations is applied to a system which has been simulated on an electronic analog computer, voltages are measured at the outputs and internal points of interest. Since the voltages behave in a manner analogous to the variables of the actual system, the designer thus sees what response the actual physical system will give. Changes in design can often be made by simply adjusting a potentiometer or changing a capacitor. At other times the design change can only be represented by the readjustment of a transfer function generator, a rather tedious task.

Figure 2 shows an electronic analog computer diagram for the study of the power system proposed by Oklahoma State University (3) and described in Chapter IV. There are three function generators needed to represent the nonlinearities of the propeller, the generator-electrolysis cell combination, and the fuel cell-inverter combination. Two additional function generators are needed to generate the input functions, the wind velocity and the load demand, as functions of time. For function generators of any reasonable size, i.e. the common size with 12 break points or even a special unit with 100 break points, these could provide only a very rough approximation to the input functions which have 8760 points each.

Digital Simulation

Soon after the advent of the electronic analog computer, there were some digital machines built to perform as analog machines but using digital integration to improve accuracy. Computer Research Corporation's model number 105 is an example of these machines which were made in the late 1940's and early 1950's. They were called
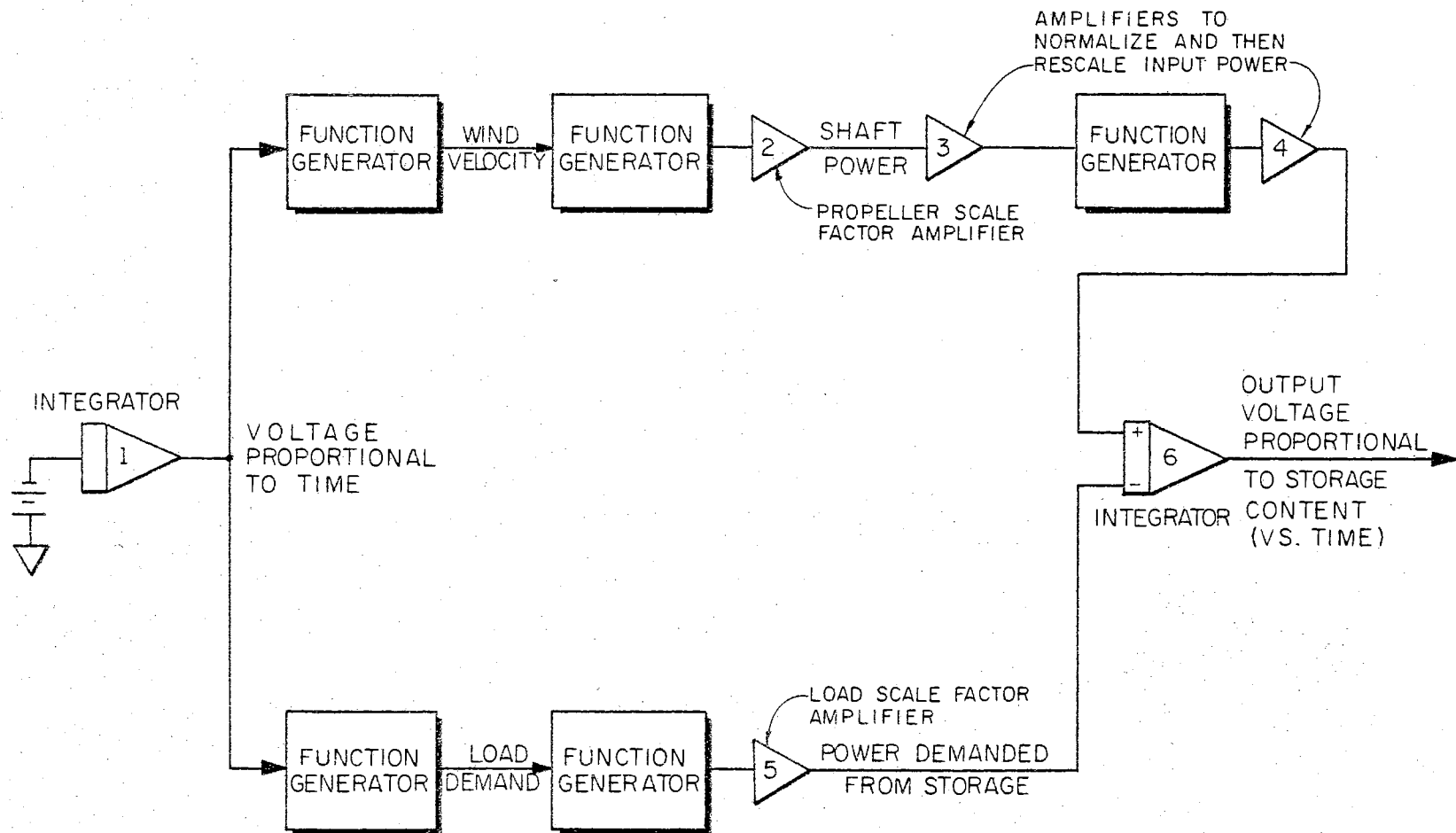
Figure 2. Proposed Block Diagram for Electronic Analog
Computer Simulation of Power System

digital differential analyzers.

The first published account of the use of a general purpose digital computer to model an analog computer was by Selfridge (24) in 1955. The two primary reasons for programming a digital computer to perform as an analog computer are to obtain greater accuracy and to obtain greater capacity for larger problems. Much larger problems can be programmed on a digital computer than on an analog computer using a comparable amount of equipment. Following Selfridge, there was first a trickle and then a stream of simulation languages designed to permit the use of a digital computer in the simulation of continuous systems. Linebarger and Brennan (25) in 1965 tabulated this growth of simulation languages. Their table is reproduced as Table 1. Since then the stream has become a flood as each computer manufacturer made software provisions for digital simulation and then many users developed variations for their particular problems.

The simulation languages developed by the manufacturers tend to be general purpose in nature and have many ramifications available to the user who is willing to study the language in depth. CSMP, Continuous System Modeling Program, which was first developed by IBM in 1966 for their 1130 and adapted to their 360 in 1967 is an illustration of this (26). The variations of these languages developed by the users tend to be special purpose in nature and thus quite narrow in application.

Hybrid Computation

Present state of the art limits even the best analog computer components to about 0.001% accuracy whereas a digital computer is limited in accuracy only by the number of digits used in the calculations,

TABLE I

DIGITAL SIMULATION LANGUAGES FOR CONTINUOUS SYSTEMS

Name	Meaning of Name	Date	Author	Originating Organization	Digital Computer Written For	Integration Routines	Immediate Ancestor	Remarks
--		55	R. G. Selfridge	USNOTS Inyokern	IBM 701	Simpson's Rule	None	Daddy of them all
DEPI	Diff. Eqn. Pseudo Code Interpreter	57	F. Lesh	Jet Propulsion Lab	Burroughs 204	4th Order Runge-Kutta		Expanded & Improved Selfridge's Work
DIDAS	Digital Differential Analyzer Simulator	57	G. R. Slayton	Lockheed Georgia	IBM 704	Rectangular	None	Simulates A DDA
ASTRAL	Analog Schematic Translator to Algebraic Language	58	Stein, Rose & Parker	Convair Astronautics	IBM 704	Runge-Kutta	None	1st Compiler Language Invented Sorting
DEPI-IV	704 Version of DEPI	59	J. R. Hurley	Allis-Chalmers	IBM 704	4th Order Runge-Kutta	DEPI	Improved Version of DEPI for IBM 704
DYANA	Dynamics Analyzer	59	T. J. Theodoroff	Gen. Motors Research Lab	IBM 704	Rectangular	None	Mechanical System Dynamic Analyzer FORTRAN Base Language
BLODI	Block Diagram Compiler	61	Kelly, Lochbaum, & Vyssotsky	Bell Labs	IBM 704 & 7090	None	None	Block Simulator For Signal Processing Devices, Compiler
DYSAC	Digitally Simulated Analog Computer	61	J. J. Skiles & J. R. Hurley	Univ. of Wisconsin	CDC 1604	4th Order Runge-Kutta Preset ΔT	DEPI-IV	Rewrite of DEPI-IV Includes Plotter-Interpreter
DYNASAR	Dynamic Systems Analyzer	62	V. H. Lucke Y. V. Robertson A. D. Jones	Gen. Elec. Evendale, Ohio	IBM 704 & 7090	Adams-Moulton 4 Point Predictor Corrector		Error Bound. Automatic ΔT Adjustment. Sort Routine Interpreter
PARTNER	Proof of Analog Results through Numerically Equ. Routine	62	R. F. Stover	Honeywell Aero Div.	IBM 650 H-800? 1800	Trapezoidal or Rectangular	None	Originally Used to Check Analog Results Seq. Updating
DAS	Digital Analog Simulator	63	R. A. Gaskill	Martin, Orlando	IBM 7090	Rectangular	DEPI & DYSAC	Simple to Use Requires Manual Sorting Compiler
JANIS		63	R. G. Byrne	Bell Tel. Labs	IBM 7090	Rectangular	None	Manual Sorting-Build Own Blocks in FORTRAN Compiler
DIAN	Digital Analog Simulator	63	Farris & Burkhart	Iowa State Univ. Ames, Iowa	IBM 7074 7090-94	Rectangular	None	Chem. Engr. Simulations. Uses DDA Integration Scheme
COBLOC	COdap Language Block Oriented Compiler	64	R. M. Janoski	Univ. of Wisconsin	CDC 1604	Various Schemes Being Tried	DYSAC	Compiler in COdap Language. Simulates Hybrid
FORBLOC	FORTRAN Compiled Block Oriented Sim. Prog.	64	W. O. Vebber	Univ. of Wisconsin	Any Machine Using FORTRAN Compiler	Trapezoidal	DYSAC	Includes Printer, Plotter; Easy to Add New Routines
HYBLOC	Hybrid Computer Block Oriented Compiler	64	J. R. Hurley	Allis-Chalmers & Univ. of Wisconsin	IBM 709-7090-7094	4th Order Runge-Kutta Preset ΔT	DYSAC	Compiler in FAP Simulates Hybrid on 7090
MADBLOC	MAD Language Block Oriented Compiler	64	V. C. Rideout L. Taverini	Univ. of Colorado	IBM 7090	Trapezoidal	DYSAC	MAD Language Statements with blocks. External function ability
MIDAS	Modified Integration DAS	64	Harnell, Sansom, Warshawsky	Wright-Patterson AFB Ohio	FORTRAN II 7090-94 FORTRAN IV 7040-7094	5th Order MILNE-R-K Start Optimizes ΔT During Run	FROM DAS in 1963	Automatic Sorting Interpreter
ENLARGED MIDAS	--	64	G. E. Blechman	North Amer. Aviation S & ID	IBM 7090	MIDAS	MIDAS	Expanded MIDAS Component Set
PACTOLUS	River in which MIDAS got rid of the Golden Touch Bit	64	R. D. Brennan	IBM Research Lab. San Jose, Calif.	IBM 1620	2nd Order Runge-Kutta Constant T	MIDAS	Plotter, Easy to use Operator Control of Simulation
PLIANT	Procedural Language Implementing Analog Techniques	64	R. Linebarger W. Y. Syn A. H. Hoffman	IBM Develop Lab., San Jose	IBM 7090	Trapezoidal	JANIS	FORTRAN Statement Ability Together with Block Notation. User, Defined Blocks; Plotter
SCADS	Sim. of Combined Analog Digital Systems	64	J. Strauss W. Gilbert	Carnegie Inst. Tech.	G-20	4th to 6th Order Pred. Corr.	--	Used for Grad. Research in Control Systems
EASL	Engr. Anal. & Simulation Language	64	Sashkin & Schlesinger	Aerospace Corp.	7090-94	Runge-Kutta	--	On-Line Console Operation
SIMTRAN	Simulation Translator	64	W. J. Henry	Weapons Research Estab. Salisbury, Australia	7090	2nd Order Runge-	--	Change Elements without Recompilation
SLASH	Simulated Hybrid Computer	65	J. Funk	USAF Academy	B-5000	Runge-Kutta Milne	MIDAS	ALGOL Based Program
MIMIC	--	65	Harnell, Sansom, Peterson	Wright-Patterson AFB	7090-94	Milne	MIDAS	Follow on to MIDAS
DES-1	Diff. Eqn. Solver	65	Lavine	Scientific Data Systems	SDS 9300	$ Available	None	1st Complete Sim. System with Console
DSL/90	Digital Sim. Language	65	Linebarger, Syn, Wyman	IBM Dev. Lab. San Jose	7090-94	Available	PLIANT	Algebraic, Block Notation, User Blocks, Plotter

i.e. by the size of the machine. Korn and Korn (21) compare the two types of computers with regard to cost for various accuracies and the digital computer is superior whenever precision is needed.

The digital computer makes calculations one at a time whereas all units of the analog computer operate simultaneously. A digital computer is a serial machine while an analog computer is a parallel machine. Thus, in many situations, the analog computer is faster than the digital computer.

Since each type of computer is superior in some ways, it was suggested that the two be combined in such a way that each computer would operate in its sphere of superiority. This combination was realized by using analog-to-digital and digital-to-analog conversion equipment at the interface between the computers. The combination is called a hybrid computer.

Historically, analog-to-digital and digital-to-analog converters were common in textbooks in 1950 but such converters were used to interpret data used by or output from a single machine (27). About 1954 the combination of analog and digital computer equipment began to appear in the literature (28). By 1957 the idea had become widespread and has continued to grow (29,30). There were separate sections devoted to recent developments in the hybrid computer field of the 1967 and 1968 Conference Proceedings of the American Federation of Information Processing Societies.

Howe (31) suggests that hybrid computers are well suited for search techniques since so many points may be computed rapidly that a "brute force" technique may be used to assure a global minimum (or maximum) by computing the solution at each point on a grid which

encompasses the area of interest.

Burkhart (32) noted the areas of superiority of hybrid computers in a panel on hybrid computers in education thus, "Hybrid computers should be emphasized in those areas where they have definite superiority over analog and digital computers -- for example, in optimizing and search procedures."

A hybrid computer is well suited to the problem considered in this research effort. If a hybrid facility of sufficient size had been available, it should have been used for implementing the grid search technique suggested by Howe. The initial problem layout should be similar to that for the analog computer. See Figure 3. For the hybrid machine, the time generator should be the internal clock of the digital machine; also, the wind velocities and load demands should be tables stored in the digital memory. The remaining portions should be analog. The digital computer would control various gains and would be programmed to provide iterative solutions in order to cover the grid rapidly.

DIGITAL
EQUIPMENT

ANALOG EQUIPMENT

AMPLIFIERS TO
NORMALIZE AND THEN
RESCALE INPUT POWER

TABLE
OF
WIND
VELOCITIES

WIND
VELOCITY

D-TO-A
CONVERTER

PROPELLER
TRANSFER
FUNCTION

SHAFT
POWER

GENERATOR-
ELECTROLYSIS
CELL
TRANSFER
FUNCTION

PROPELLER
SCALE FACTOR

INTERNAL
CLOCK

OUTPUT VOLTAGE
PROPORTIONAL
TO STORAGE
CONTENT
(VS. TIME)

TABLE
OF LOAD
DEMAND

LOAD
DEMAND

D-TO-A
CONVERTER

RECIPROCAL OF
FUEL-CELL INVERTER
TRANSFER FUNCTION

LOAD SCALE FACTOR

POWER DEMANDED
FROM STORAGE

Figure 3. Proposed Block Diagram for Hybrid Computer Simulation of Power System

CHAPTER III

INTRODUCTION TO GPSS (GENERAL PURPOSE SIMULATION SYSTEM)

The digital computer does not always have to be programmed to op-
erate as an analog computer in order to simulate a physical system.
Discrete system simulation is an important part of computer application
in industry today. This is seen by noting the variety of applications
represented by about 80 papers presented at the Second Conference on
Applications of Simulation (33). These papers covered topics ranging
from manufacturing lead times to human systems and from the New York
City Police Department response system to a discrete biological simula-
tion of the population regulation of turtles. The most prominent
language used in these studies was GPSS (34) with Simscript (35) and
Fortran (36) being used for most of the remaining studies. Simula and
Algol were mentioned as being widely used in Europe and the Soviet
Union.

Suitability of GPSS to This Study

The normal use of an analog computer, or a digital computer
programmed to operate as an analog computer, is to simulate a continu-
ous system. Also, the normal use of a digital computer programmed by a
discrete simulation language is to simulate a discrete system. How-
ever, in this present study, an essentially continuous system was quite
successfully simulated by a discrete system language. The reasons are

given below.

    1. There are vast amounts of wind data available from various
U. S. and foreign weather stations. These data are hourly
readings and thus are already in discrete form.

    2. GPSS is ideally suited to the gathering of statistical data
such as the percentage of time that the generator is operating
between 0 and 10% of its rating, between 10% and 20%,...,
between 90% and 100%, and above 100% (if it were made larger).
This type of data gives a large amount of insight into the
level of loading of the various system components.

    3. GPSS functions make the simulation of complex physical trans-
fer functions much easier than with analog equipment. These
GPSS functions allow linear approximations to represent quite
accurately even severely nonlinear transfer functions. Addi-
tionally, an entire GPSS function may be changed to represent
a different device by replacing only three or four cards. By
keeping the original cards one may return to the earlier
situation easily and with confidence in its repeatability.

Even though GPSS normally uses statistical distributions as out-
puts, a time record can also be obtained by using entities in the
language referred to as "savevalues" and a periodic print routine. For
these reasons GPSS was selected as the vehicle for the simulation of
this system.

GPSS or its counterpart is available for most computer installa-
tions of medium or large capacity regardless of the manufacturer of the
equipment. This particular language, GPSS, was originally written by
IBM for their own use in demonstrating to prospective customers what

performance they could expect from various combinations of computer and peripheral equipment; other computer manufacturers have similar languages available to users of their equipment. Hybrid facilities of sufficient size to simulate this system are not common yet so the author feels that the development of this simulation in GPSS will benefit more users than the hybrid simulation would have.

Fundamentals of GPSS

While this simulation does not use the strongest feature of GPSS, i.e., queueing theory, it does find other properties of GPSS to be highly desirable. The gathering of tabular data, the optional printout of savevalue data as desired, and the use of list functions are among these highly useful characteristics of GPSS. Also, the fact that component efficiencies may be functions rather than constants adds much realism to the simulation. Some of the basic entities of GPSS which are used in this simulation are presented first, then these refinements will be explained.

Some basic entities of GPSS are transactions, storages, savevalues, comparisons (tests), and variables (34). The generate and terminate commands are used, respectively, to introduce and remove transactions from the simulation. For normal applications of GPSS, a transaction would represent something tangible such as a court case to be placed on a calendar according to certain limitations, priorities, and availability of schedules. The present simulation does not attach any physical significance to a transaction; it is merely a trigger released at a predetermined time and routed in such a manner that it causes the desired actions to occur in the proper sequence. For example, a

transaction may be generated every 24 hours of simulated time and trigger a print command which produces data from all non-zero save-values to obtain a time record of energy storage content. A savevalue is simply a pigeon-hole for storing data as the simulation progresses.

Storages, as the name implies, are entities which represent physical reservoirs. Variables are defined by mathematical expressions and thus are means for performing arithmetic. Comparisons are obtained by calling for the test entity. As an illustration, consider a situation wherein a storage with a given capacity is partly filled. The transaction enters a test block which tests the energy generated to see whether it is greater than the remaining vacant space in storage. If the test determines that the energy generated is greater than the remaining space, the transaction is routed to a block which discards the energy. Otherwise, the transaction is routed to a block which places the energy into the storage.

The entities explained thus far are the simpler ones. The more complex ones such as tables, print routines, and functions are explained in greater detail.

Tabular Data

In choosing generator ratings, wind-intercept areas, electrolysis cell or fuel cell ratings, and storage capacities, the designer needs to know as much as is practical about the utilization of each of these components. Thus power flow through each element and total storage content are tabulated for study by the designer. These tables consist of columns of information such as shown in Table II. This particular tables gives information about the generator output and is defined to

TABLE II

EXAMPLE OF TABULAR DATA

Entries in Table 21600		Mean Arguments 313.446	Standard Deviation 518.299		Sum of Arguments 6770436.000	

Upper Limit	Observed Frequency	Per Cent of Total	Cumulative Percentage	Cumulative Remainder	Multiple of Mean	Deviation from Mean
0	3698	17.12	17.1	82.9	.000	-.605
1000	16407	75.96	93.1	6.9	3.190	1.325
2000	1119	5.18	98.3	1.7	6.381	3.254
3000	243	1.12	99.4	.6	9.571	5.184
4000	78	.36	99.7	.3	12.761	7.113
5000	39	.18	99.9	.1	15.952	9.042
6000	8	.04	100.0	.0	19.142	10.972
7000	2	.01	100.0	.0	22.332	12.901
8000	2	.01	100.0	.0	25.523	14.830
9000	3	.01	100.0	.0	28.713	16.760
10000	1	.00	100.0	.0	31.903	18.689

Remaining frequencies are all zero.

start at zero and tabulate data in 1000 watt intervals with a maximum

of 400 such intervals. An additional two intervals are designated to

tabulate data below and above the designated regions. Each interval

includes its upper limit but not its lower limit.

From the table it is seen that there were 21600 entries totaling

6,770,436. The average value was 313.446. Reading across the table

one finds that the generator had no output 3698 times which comprised

17.12% of the total number of entries. The cumulative percentage is

the same and the cumulative remainder is 100% minus this 17.12% or

82.9%. The next line yields the information that the generator output

was greater than zero but less than or equal to 1000 watts 16407 times

which comprised 75.96% of the total number of entries. The cumulative

percentage is 75.96 plus 17.12 which is 93.1%; this leaves a cumulative

remainder of 6.9%. The other lines contain the same information for

the other intervals. Note that the generator did not have an output,

at any time, greater than 10,000 watts so all intervals above 10,000

watts were covered by the statement "remaining frequencies are all

zero".

In some cases two tables are made with one of the tables being an

expansion of a given vital segment of the other table. The GPSS tables

are ideally suited for providing the answers to such questions as: is

it economically sound to attempt to extract the peak energy from the

wind gusts or will it be more economical to build a larger propeller

coupled to a smaller generator and thereby discard the peak energies?

This question is an important one since wind power is proportional to

the cube of the velocity. Thus, whenever the wind gusts to twice the

average velocity, the available power is increased by a factor of eight.

If a significant fraction of the total available power is contained in
these gusts then they must be included in the optimization of the gen-
erator rating and wind intercept area. For this reason tabulated data
are used primarily in determining power ratings for component sizes
while both tabulated data and the time record are used in determining
the energy storage capacity rating.

Print Routines

The tabular data obtained is automatically printed out at the end
of a simulation run but it is statistical in nature and has retained no
relationship with time. For example, the same statistical information
would come from a solar cell receiving sunlight for 12 hours of each
24 hours for 12 months and another solar cell receiving sunlight con-
stantly for 6 months and then receiving no sunlight for the other 6
months. However, a much smaller energy storage capacity would be re-
quired to supply a load for the 12 hour dark period than for the 6
month dark period if it is assumed that each storage is refilled during
its period of sunlight. This is an extreme illustration (though quite
possible with today's satellites) but it does point out the usefulness
of having a time record to accompany the statistical data.

Data storage and print routines have been devised for maintaining
the desired time record of total storage content. Any other desired
information could be similarly recorded by these techniques. The de-
sired data are stored and printed out periodically at predetermined
times. This periodic printout is necessary since there are only 400
storage locations, called savevalues, available unless a reallocation
is made. These routines are quite versatile in that data may be stored

at each 0.1 hour if desired or at other times such as each hour, each
hour for every Friday (or Monday, etc.), each hour for some specific
month, or perhaps at 6:00 a.m. to begin each day. Figure 4 is a plot
of the total energy stored at 6:00 a.m. of each day for three months.

List Functions

A normal nonlinear function is specified by pairs of coordinates.
That is to say that an x value is given and then the corresponding y
value is given. In GPSS the function is evaluated at a given value of
x, say x_o, by comparing x_o with the x of the first point, then the
second point, then the third, etc. until two adjacent values of x are
found with one smaller than x_o and one larger than x_o. The correspond-
ing value for y_o is then computed by linear interpolation if a contin-
uous function has been specified or is taken to be the y value corres-
ponding to the larger x value if a discrete function has been specifi-
ed. The list function, however, is a particularly good function to
use with large amounts of data since only the y values are read into
the computer; the x values are assumed to be the positive integers in
order. That is to say that the first y value is coupled with x equals
one, the second y value with x equals two, etc. Thus a list function
occupies only half as much space in the computer as the other func-
tions. A second advantage is a much faster look-up time for evaluating
the function. For a given integral value of x, say x_o, the correspond-
ing value for y is selected by its position in the list without any x
comparisons. These two characteristics of list functions have allowed
the simulation to cover longer periods of simulation time for a given
amount of computer time than would have been possible with the other
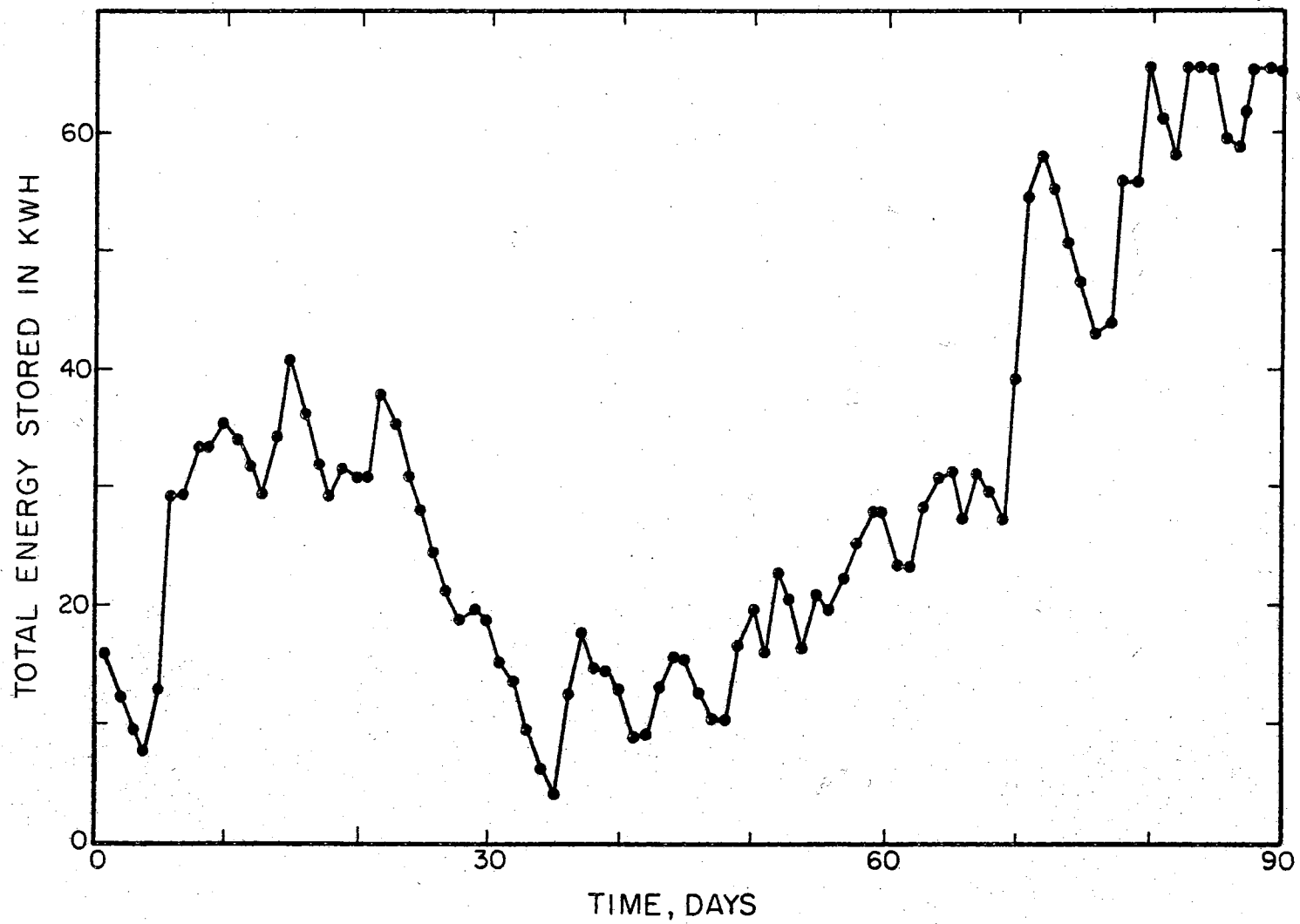
Figure 4. Time Record of Total Energy in Storage at 6:00 a.m.
of Each Day for Three Months

functions.

Transfer Functions

One of the noteworthy aspects of this simulation is the ease with which transfer functions may be simulated as functions rather than constants. The wide range of input power causes the generator efficiency to vary a rather significant amount. This same situation causes the wind intercept device, the electrolysis cell, the fuel cell, and any other devices such as pumps or burners to have varying efficiencies. Thus, the fidelity of the simulation is greatly improved by using these transfer functions.

This brief introduction to GPSS is presented for the orientation of the reader who is inexperienced in this particular simulation language.

CHAPTER IV

DESIGN PROCEDURE

The design procedure developed by this research effort applies to
any system which can be represented by the block diagram of Figure 5.
The input quantity is acted upon by any number of transfer functions in
series until it has been transformed into a form suitable for storing.
The storage output is acted upon by the necessary transfer functions to
transform it into a usable form at the point of use. Although this
effort is concerned with power systems, the procedures are equally
applicable to such a diverse process as mining ore, shipping and stor-
ing it, then processing and using it. For this mining problem, the
transfer functions would not all be output magnitude versus input mag-
nitude; some would be delay times versus magnitude. In any case the
restrictions upon the transfer functions are few. The source and usage
must be known functions; the transfer functions, the A's and B's, must
be known single valued functions. Extreme nonlinearities in the trans-
fer functions are no problem.

The design procedure is a combination of engineering judgment,
approximate calculations, and exact computer solutions. This combina-
tion is commonly referred to as computer-aided design. Thus the engi-
neer will use whatever information he knows about the system to define
the problem, set up the system model, select the quantities to be var-
ied during the optimization process, set the limits on these variables,

INPUT SOURCE — A_1 — A_2 --- A_n — STORAGE — B_1 — B_2 --- B_m — USE

◯ TRANSFER FUNCTIONS

Figure 5. Block Diagram Representation of the System to be
Used With Computer-Aided Design

and then choose a region which may offer the most promising range for each variable. After the use of knowledge from his experience and the approximate calculations, he then uses the computer for refinement of the data. Finally, based upon the results of the computations, he exercises his engineering judgment to select the final design values for the components. This design procedure is shown in block diagram form in Figure 6.

Preliminary Considerations

Model System

The design procedure has been developed for the block diagram of Figure 5. The first step is to ascertain whether the system to be designed can be modeled by this figure. In Figure 5, any number of nonlinear transfer functions may be included in the A series, any number in the B series, and zero is a perfectly acceptable capacity for the storage. Any A or any B function may be a constant, may be a linear or nonlinear function of input magnitude, may vary as a function of the independent variable, or may be a statistical function with a random number generator determining its value. For those systems which may be modeled by Figure 5, the procedure outlined by Figure 6 may be used to arrive at a satisfactory conclusion regarding the design of the system.

Define Problem

The first step in defining the problem is to determine what the design criterion is. Often there will be multiple considerations so one must use judgment in evaluating their relative significance. The engineer must consider many facets of the problem other than the
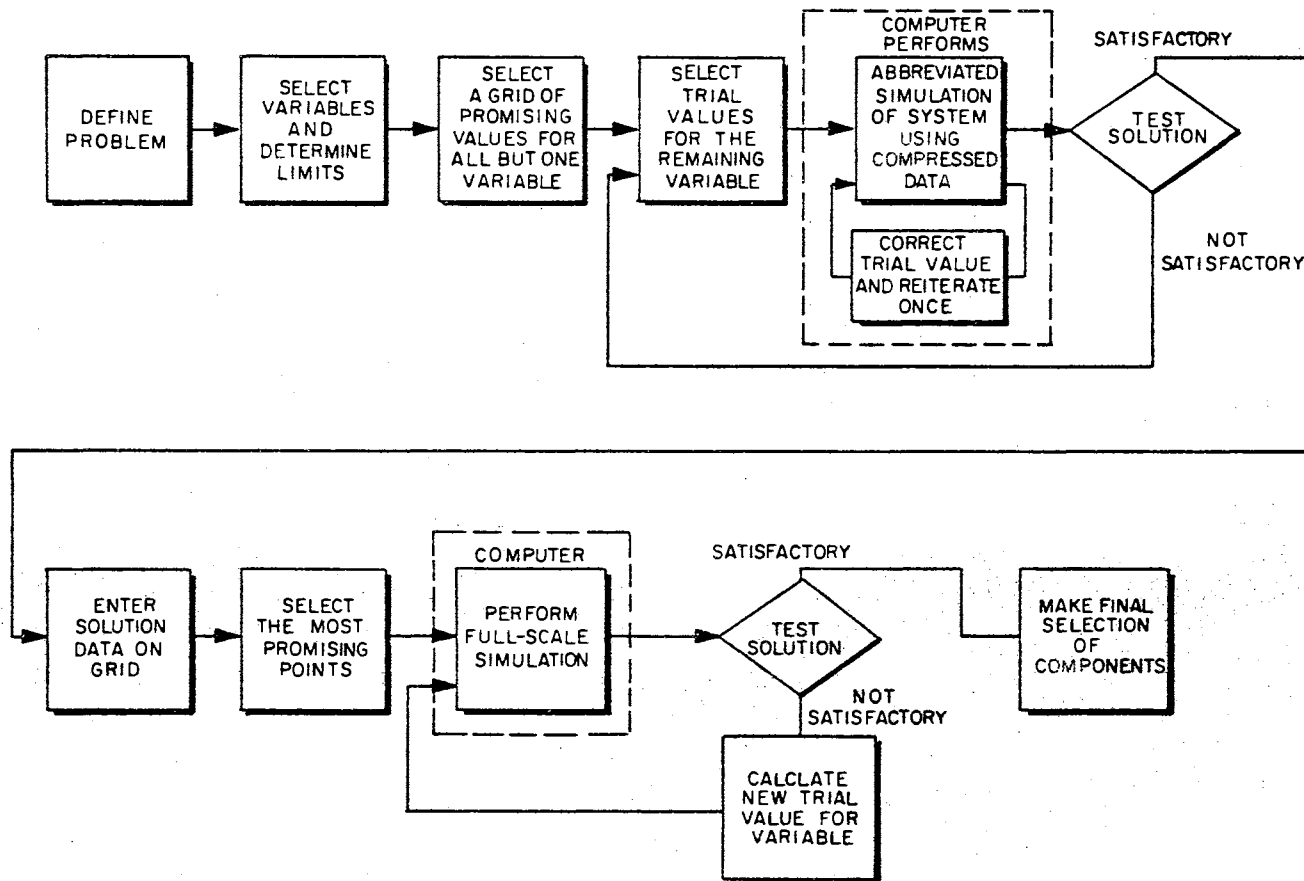
Figure 6. Block Diagram of Computer-Aided Design Procedure

technical. Often the economics of the device are the most important consideration but one must not overlook the social and political implications in certain situations. Thus the engineer must weigh the considerations, define the acceptable alternatives, analyze each, and select the most promising course of action. Defining the problem is no small task; when one has defined the problem he is well along the path toward its solution.

Select Variables and Determine Limits

Each problem will have its own particular characteristics which may lead to minor variations of the design procedures but there are some general characteristics which are universally applicable. For example, if it is required that the output demand, or use, is always met, then the sizes for the elements represented by the output transfer functions, the B's, must be sufficiently large to meet the maximum demand but need be no larger. This fact establishes these transfer functions so they will not need to be variables. Since the source is known, the only design variables are the storage capacity and the size of the devices represented by the A transfer functions. In order to vary the size, the designer assumes that a larger device of the same type will have the same shape transfer function but with the magnitudes scaled.

Minima for the Variables

Each of the variables will have a minimum value below which the system will not perform the required task. For example, there may be periods during which the input is zero. If an output demand occurs

during one of these periods, that demand must be supplied from the backlog in storage. If the storage capacity were zero, there would be no backlog so the system would not perform correctly. Therefore, zero would not be an acceptable minimum value for storage. For this reason, there should be a preliminary investigation of each variable to determine its minimum possible value.

The minimum value possible for each device may be determined by assuming the most favorable conditions possible for its operation and calculating the resulting size required. This calculation does not need to be exact since it will be used as an approximate limit or guideline and not as an inflexible boundary.

Maxima for the Variables

There is a good chance that very large values for the variables may be ruled out individually. Each one should be considered on its own merits regarding its effects on the system when it is increased without bound. Why should a power company build a reservoir capable of storing twenty million acre-feet of water if rainfall and runoff figures indicate that a half million acre-feet is all that can ever be stored there? Engineering experience and a few calculations will generally determine the upper practical limit on the size of the components.

A Grid of Promising Values

The reason for the determination of the approximate limits for the upper and lower bounds on the component sizes is to make the computer effort more productive. By determining these limits one has reduced

the region that must be investigated by the computer.

At this point in the development of the computer-aided design procedure, a choice had to be made regarding the type of computer investigation to be made. The choice was between a minimum-seeking program and a grid-search program. The minimum-seeking program would take an initial guess for each variable and refine these values until some predetermined design criterion had been met. The grid-search program would produce a solution for each point of the n-dimensional grid. In either case, the solutions would be composed of the size of each variable and a calculation of the quantity to be minimized (or maximized). The grid-search program was selected since it provides much more information to the designer and allows a much more flexible design using engineering judgment.

In order to cover the region of interest systematically, the engineer may establish a course n-dimensional grid of the region and progressively refine the grid in the most productive area. An n-dimensional grid is made since there are n plus one variables; the computer establishes the value of the last variable. Figure 7 illustrates the two simplest grids and how they might be addressed to the most promising region.

Trial Values for the Remaining Variable

The engineer must rely upon his experience a great deal in selecting the initial values for the trial values for the remaining variable which does not appear on the search grid. The previous calculations of limits plus the estimate of the effects of any nonlinearities of the other variables will help in this initial selection.
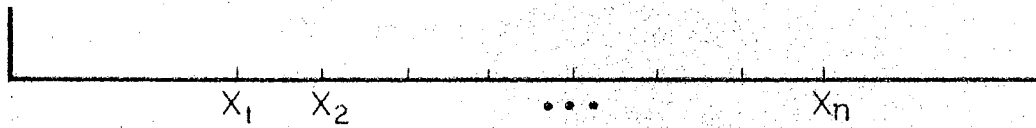
(a) ONE-DIMENSIONAL GRID
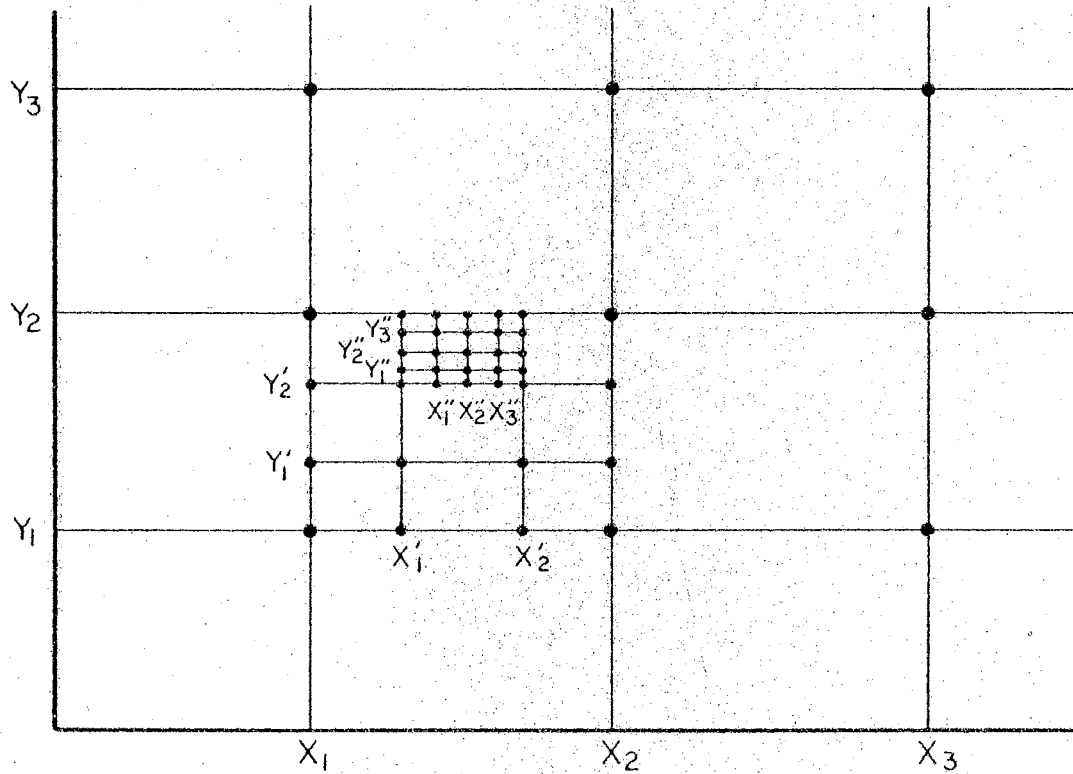
(b) TWO-DIMENSIONAL GRID

Figure 7. Examples of One- and Two-Dimensional Search
Grids Showing a Grid Refinement

The initial trial value will quite probably not be the correct

value for this variable so a second trial value must be selected after

the computer has made a simulation, an approximate correction, and an

iteration to provide a second simulation at each point on the grid. If

the simulations indicate that the value is close, a linear interpola-

tion will normally produce a second trial value that is very close to

the correct one. If the value is not very close, a linear interpola-

tion may be coupled with the anticipated effects of the nonlinearities

to obtain the second trial value.

Computer-Aided Study

Computer Simulation

Since a simulation must be performed at each trial for each point

of the search grid, a more gross or reduced simulation would give rela-

tive data to determine the location of the most desirable points on

the grid. A great amount of computer time can potentially be saved

using this technique. A full simulation can then be made for only

those few points which show the most promise.

The abbreviated simulation may be obtained in several ways. A

full simulation may be performed on every nth point or the data may be

averaged by groups of n. Also, some of the refinements of the simula-

tion may be omitted for the first rough or abbreviated simulation. A

combination of reducing the input data and simplifying the simulation

results in an even greater saving in computer time. Both techniques

are used in the computer program in this computer-aided design proce-

dure.

Two computations are made per point on the grid. A simulation is

made with the initial trial value of the variable omitted from the grid,
a linear correction is applied to this trial value, and a second simu-
lation is made with this corrected value of the variable. This process
is repeated for other points on the grid and the computer prints out
the results. These solutions are used by the designer to make further
judgment in the region of simulation.

Test Solution

The computer solutions for each point on the grid are tested for
sufficiency. A solution is considered to be satisfactory when the de-
mand at the output has been met at all times without providing more
reserve energy storage than necessary for emergencies. For those
points where the solution is not satisfactory, a new trial value is
selected for the variable not on the grid and two more simulations are
made. Whenever a solution is satisfactory at a point the data for
that solution are entered on the search grid and that point is omitted
from future abbreviated simulations. Normally only a few passes
through the computer are needed to complete the data on the search
grid.

Selecting the Points for the Full-Scale Simulation

After the search grid data have all been acquired using the abbre-
viated simulation, the grid is examined for significant results. If
the minimum occurs at one edge of the grid, then the grid must be ex-
tended in that direction to insure that a true minimum has been obtain-
ed. If the minimum is quite sharply defined, then only a few points
in the immediate vicinity need be considered for the full-scale

simulation. If the minimum is quite broad, then secondary considerations must be made. After due consideration, a few points normally will offer the most promise for an optimum solution based on minimization and engineering judgment where needed.

Full Scale Simulation

At this point in the design procedure a simulation is made that is as nearly realistic as possible. The results of this simulation will then be used to choose the components of the physical system.

The solution from the full scale simulation is checked for sufficiency using the same test as for the abbreviated simulation. If test is not satisfactory, a new trial value is calculated for the variable not on the search grid and the simulation is repeated. If the solution is satisfactory, it is set aside for final consideration.

Final Selection of Components

Whenever satisfactory solutions have been obtained for the points on the grid selected for full scale simulation, the designer is ready to make the final selection of components. These computer solutions can only aid him by giving him additional information based upon the data and programs entered into it. He must use engineering judgment, common sense, experience, knowledge of system components, and all the information that he can gain from any source if he expects to arrive at the best possible design.

The computer solutions are studied and their significance is weighed. Then, with due consideration given to all aspects of the system, the actual physical size of each component is chosen.

CHAPTER V

ILLUSTRATIVE DESIGN OF A POWER SYSTEM

An illustrative example serves a number of purposes. It clarifies
an explanation, fills in details, fixes the procedure in the reader's
mind, and demonstrates that the process does work as presented. The
example presented in the following pages is given in considerable de-
tail in order to accomplish each of these objectives. The power system
to be designed as an illustrated example is shown in Figure 8.

At the time that this project was originally undertaken there was
a need for power systems with capacities ranging from a fraction of a
kilowatt to a few kilowatts. Evans (38) indicated a need for a design
procedure to produce optimum generation and energy storage systems for
use at isolated marine stations along the coastal regions of the United
States. He indicated that the technique of matching energy generated
with energy used is very time consuming when accomplished by graphical
techniques.

The other uses for power systems in this range were proposed by
McCollom (4) and are shown in Figure 9. The irrigation load would be
concentrated during three or four months of the year and would be con-
stant during its period of operation. The grain drying facility would
have about the same characteristics. A combination of these two loads
would provide more utilization of the equipment by providing a load
for a longer period of time each year. However, either of these two

ELECTRICAL WIRES

HYDROGEN
STORAGE
TANKS

PROPELLER

ELECTROLYSIS
CELL

POWER TRANSMISSION
LINES TO LOAD

SHAFT

FUEL
CELL

INVERTER

INPUT   OUTPUT

ELECTRICAL
GENERATOR

OXYGEN

AIR

WIND

INPUT PORTION

OF

POWER SYSTEM

OUTPUT PORTION

OF
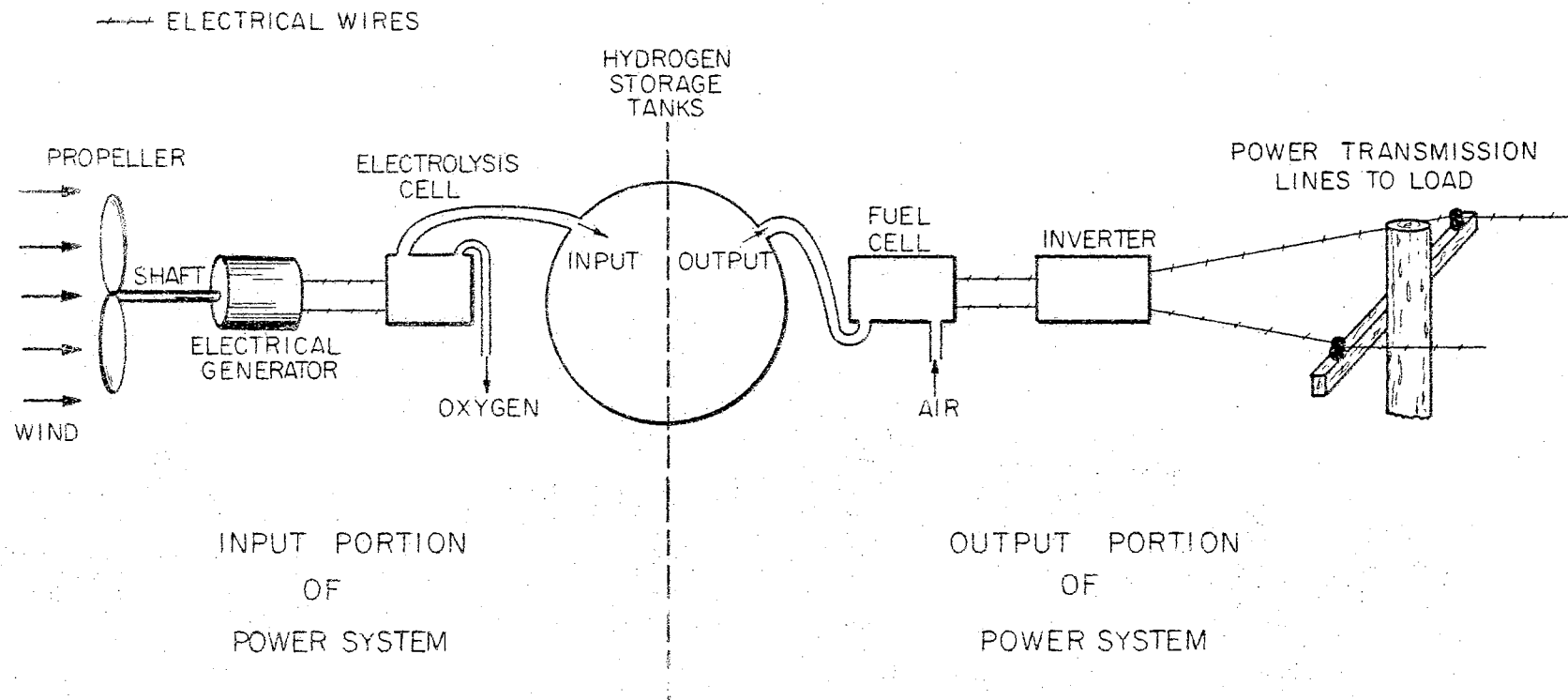
POWER SYSTEM

Figure 8.   Unconventional Power System Using Energy Storage Used as an
Illustrative Example for the Computer-Aided Design
Procedure

41
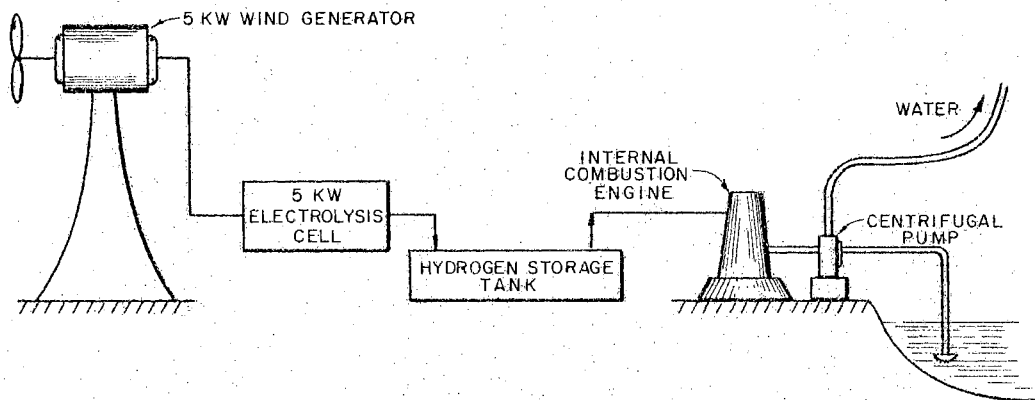
(a) UNCONVENTIONAL SOURCE SUPPLYING AN IRRIGATION SYSTEM
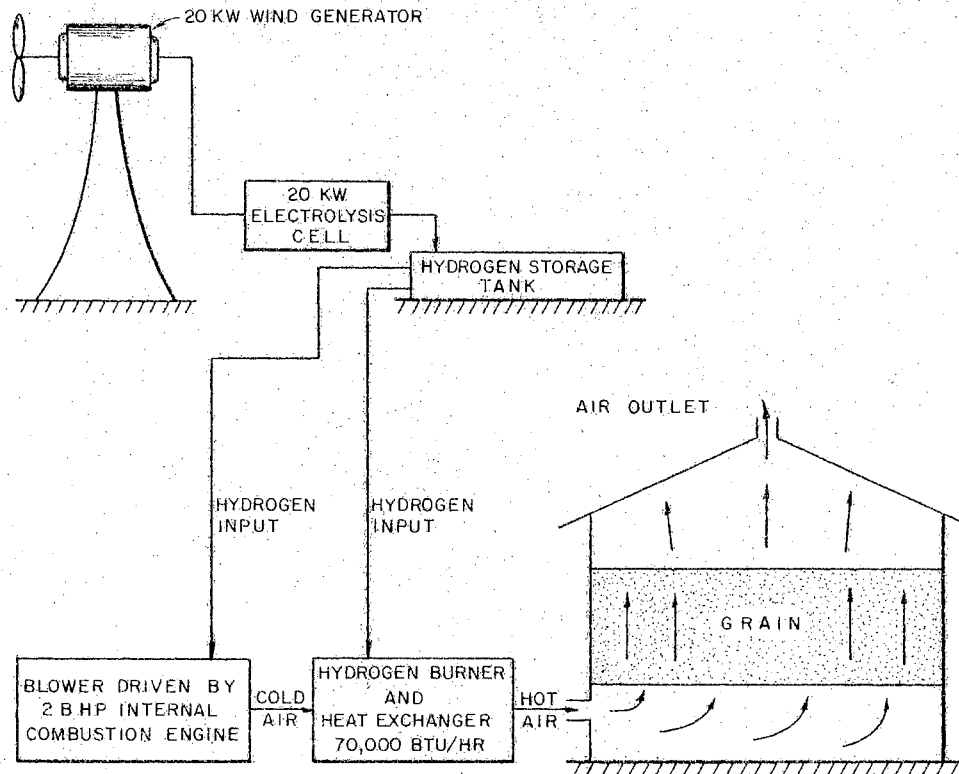
(b) UNCONVENTIONAL SOURCE USED FOR DRYING GRAIN

Figure 9. Two Possible Applications for the Use of
Energy From an Unconventional Source

individually or the combination would have the characteristic of being used only a portion of the time and being used to capacity whenever it was in use. The load chosen to illustrate the design procedure should be one that tests the procedures more fully than these loads will.

Preliminary Considerations

Since the actual load variations for use in a developing country are not known, the problem is defined such that system variations would be similar to the load variations of a power company here in the United States but on a smaller scale. The actual load demand for the Public Service Company of Oklahoma for 1965 was available so it was scaled down from a maximum value of 1000 megawatts to a maximum of 1000 watts and used to represent the load demand for the example system.

The choice of load for the system fixes the components of the output portion of the power system of Figure 8. The sizes of the output lines from the storage tank, the fuel cell, the inverter, and the transmission lines are all fixed by this load.

The next step in the design procedure is consideration of the quantities to be varied and the determination of their possible limitations and most promising regions to be investigated. Figure 10 shows a block diagram of the system including the variables to be considered. The variables are the size of the propeller, the capacity of the generator and electrolysis cell, and the volume of the energy storage unit. The generator and electrolysis cell are considered to be just one variable since the two would normally have the same maximum rating.

ELECTROLYSIS   HYDROGEN   FUEL   TRANSMISSION
PROPELLER GENERATOR   CELL   GAS   CELL   INVERTER   LINE
TRANSFER TRANSFER TRANSFER   STORAGE   TRANSFER TRANSFER TRANSFER
WIND   FUNCTION FUNCTION FUNCTION   TANKS   FUNCTION FUNCTION FUNCTION   LOAD

USEFUL
ENERGY   (A1)   (A2)   (A3)   STORAGE   (B1)   (B2)   (B3)   USE
SOURCE

V_1 V_2 V_3
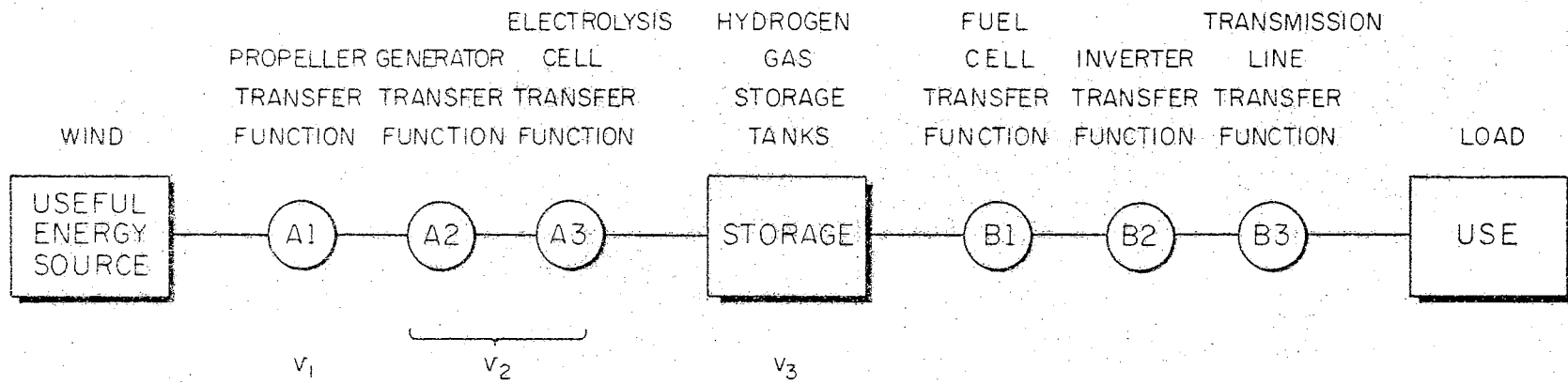
Figure 10. System Block Diagram, Showing the Design Variables, v_1,
v_2, and v_3, for the Computer-Aided Design of the
Example Power System of Figure 8

The Propeller - Energy From Wind

Wind and sunlight are perhaps the two most universally available unconventional sources of energy. At the present time the conversion device for obtaining useful electrical energy from winds is much less expensive than the conversion device for sunlight; a propeller does not cost as much as solar cells. For this reason winds were selected as the source of energy for the small, unconventional power system.

The power contained in a moving air mass is proportional to the cube of the velocity (3). This is shown by

$$P = 8.1 \times 10^{-3} V^3 \text{ watts per square foot}$$

where

(5.1)

P = power density available in the wind in watts

per square foot of wind intercept area

and

V = wind velocity in knots.

The maximum extractable amount of this theoretically available power is 59% according to Betz (7). Summers (3) gives a typical efficiency as 40%. Data for a Wincharger commerical wind generator states that charging begins at about seven miles per hour of wind velocity since friction and other losses must be overcome. These facts were used to estimate propeller characteristics. The resulting curve was approximated by straight-line segments to obtain the propeller transfer function, Function 7, used in the computer programs. Figure 11 shows both the curve and the straight-line approximation of the propeller power transfer function. Note how closely the curve is approximated by the line segments.
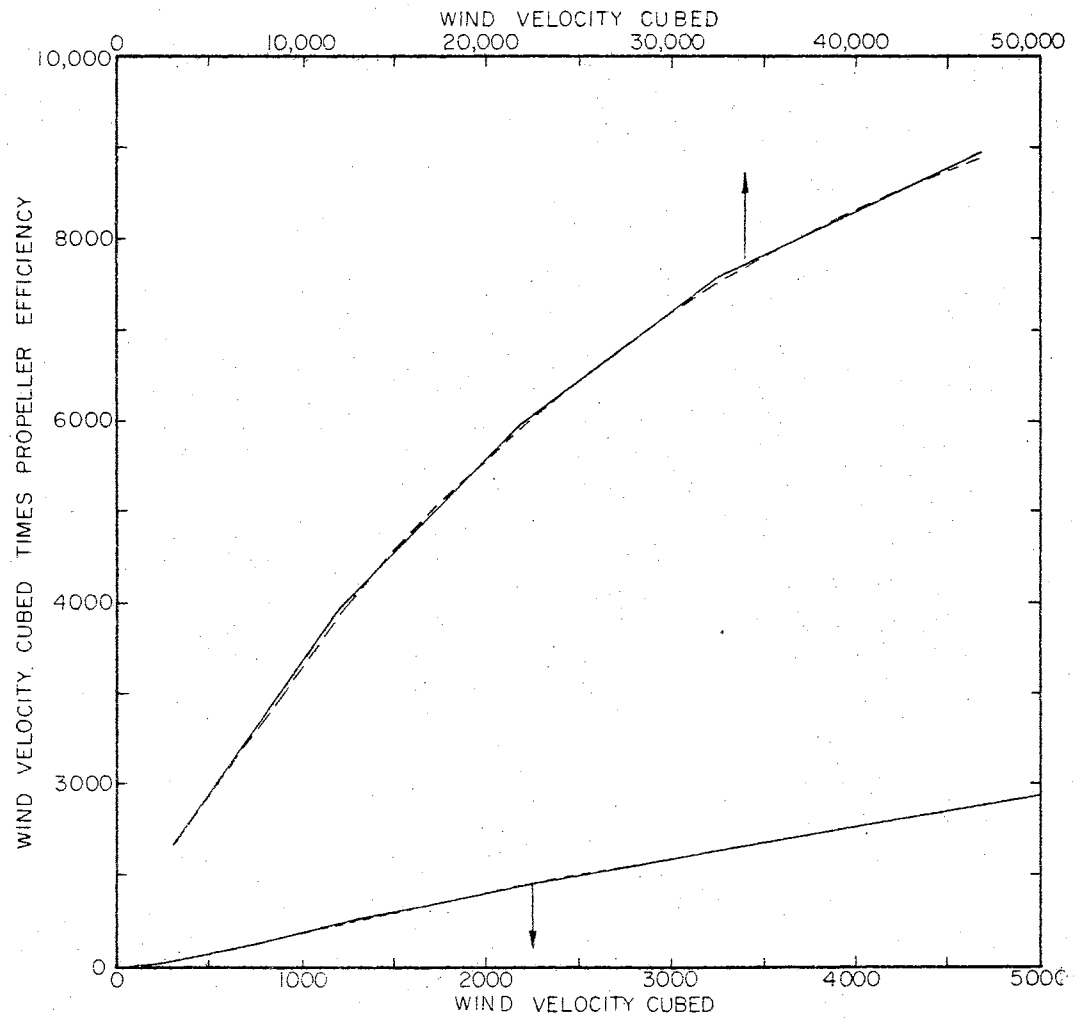
Figure 11. Propeller Transfer Function Showing Relationship
Between Theoretically Available Wind Power and
the Power Delivered to the Propeller Shaft

Cost of the propeller alone would be a comparatively small item of expense. However, the mounting tower must be included in the cost of the wind intercept device. Whereas the cost per unit wind intercept area of the propeller alone decreases quite rapidly with increasing area, the cost of the combination of propeller and tower was assumed to increase linearly with increasing area after an initial basic cost. Since local labor and material costs would influence this cost drastically, this cost function, Function 10, may be changed to fit local conditions as required. Figure 12 shows both the curve and the straight-line approximation for the combined propeller and tower cost transfer function.

Generator and Electrolysis Cell

The propeller intercepts the wind's power and converts it into rotational power in a shaft. This mechanical shaft power must be converted into a form which can be stored and readily reconverted upon demand. Several ways are available. Large power companies have pumped water from a lower reservoir to an upper reservoir storing the energy as the potential energy of the water. Other possibilities have been discussed and of these, Oklahoma State University personnel have chosen to store energy in the form of high pressure hydrogen in tanks or caverns (1,3). Thus, a generator is used to convert the shaft power to electrical power and then a high-pressure electrolysis cell is used to convert water into hydrogen and oxygen. The oxygen may be bottled and sold for other purposes but the hydrogen is stored and kept for use upon demand. Any profits from the oxygen are not included in the economics of this study.
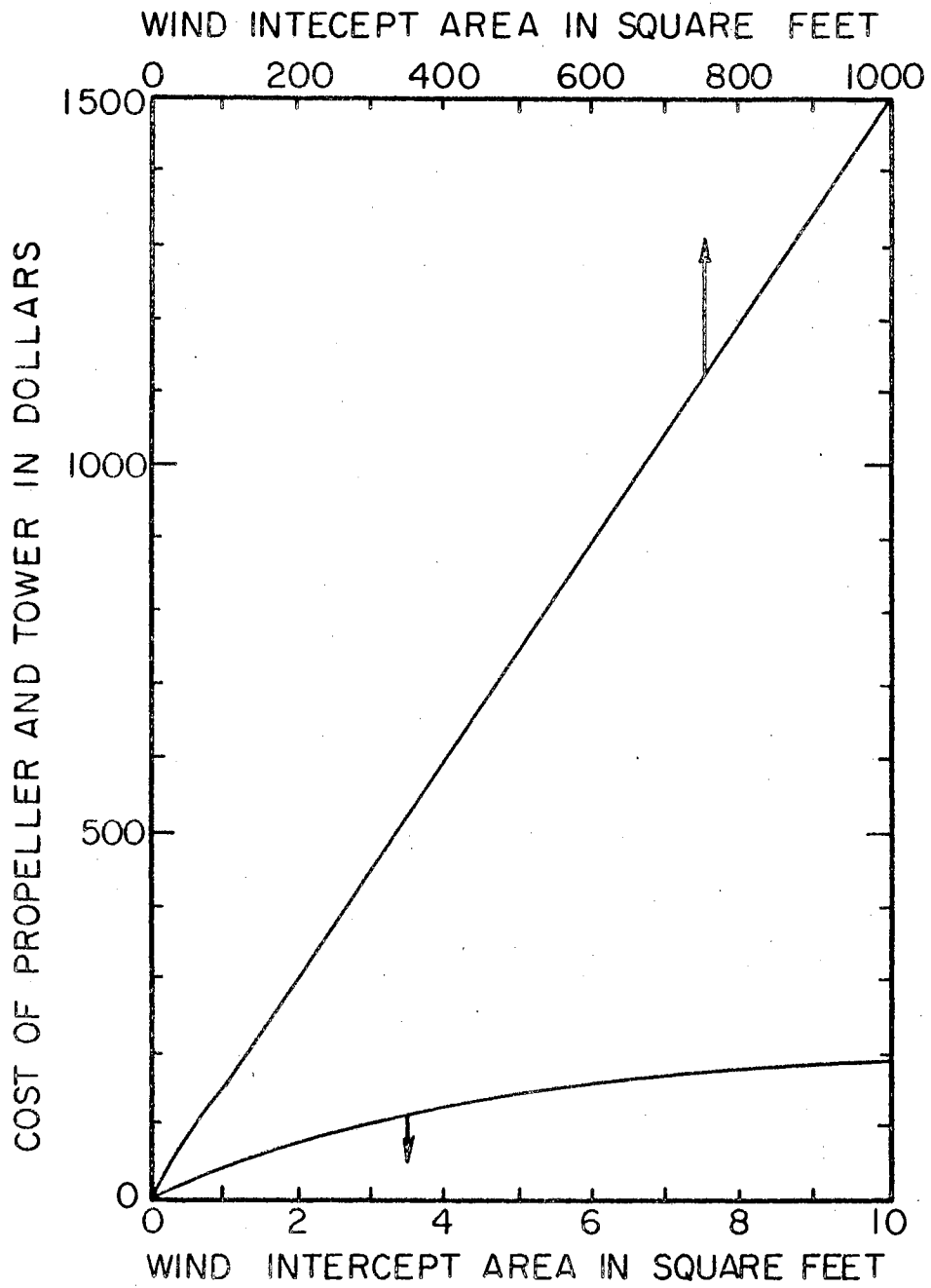
Figure 12. Cost of Propeller and Tower as a
Function of Wind Intercept Area

There were several classes of generators examined initially. The Wincharger commercial unit was found to be very rugged but very inefficient. Automobile generators were more efficient but quite heavy. Aircraft generators were both lighter and more efficient than the other two but not quite so good on both points as the final choice, an automobile alternator. Experimental investigations by Gibson (13) and the author led to the transfer function used in the computer programs, Function 5. This transfer function includes the experimental transfer of energy plus the expected losses in the energy coupling devices; either belts and pulleys or gears are the anticipated coupling devices. Because of the slow speed of the propeller and the better efficiencies of the alternator at the higher speeds, some coupling device is needed which will enable the alternator to turn at a higher rotational speed than the propeller.

The generator transfer function also includes a saturation effect which prevents any output greater than 100%. In the actual system one would expect this limiting to occur either in the coupling to the generator or at the propeller. Wincharger has an air brake attached to the propeller for this purpose; the suggested self-adjusting, variable-pitch propeller of Appendix G could be set to perform this function also. Figure 13 is a plot of electrical power out versus mechanical power into the generator.

The electrical power from the generator is applied to an electrolysis cell which breaks water into its components, hydrogen and oxygen. The characteristics of this cell were obtained from H. J. Allison in private communications and from reports (10, 11, 37). The electrolysis cell not only produces the gases, it continues to produce them
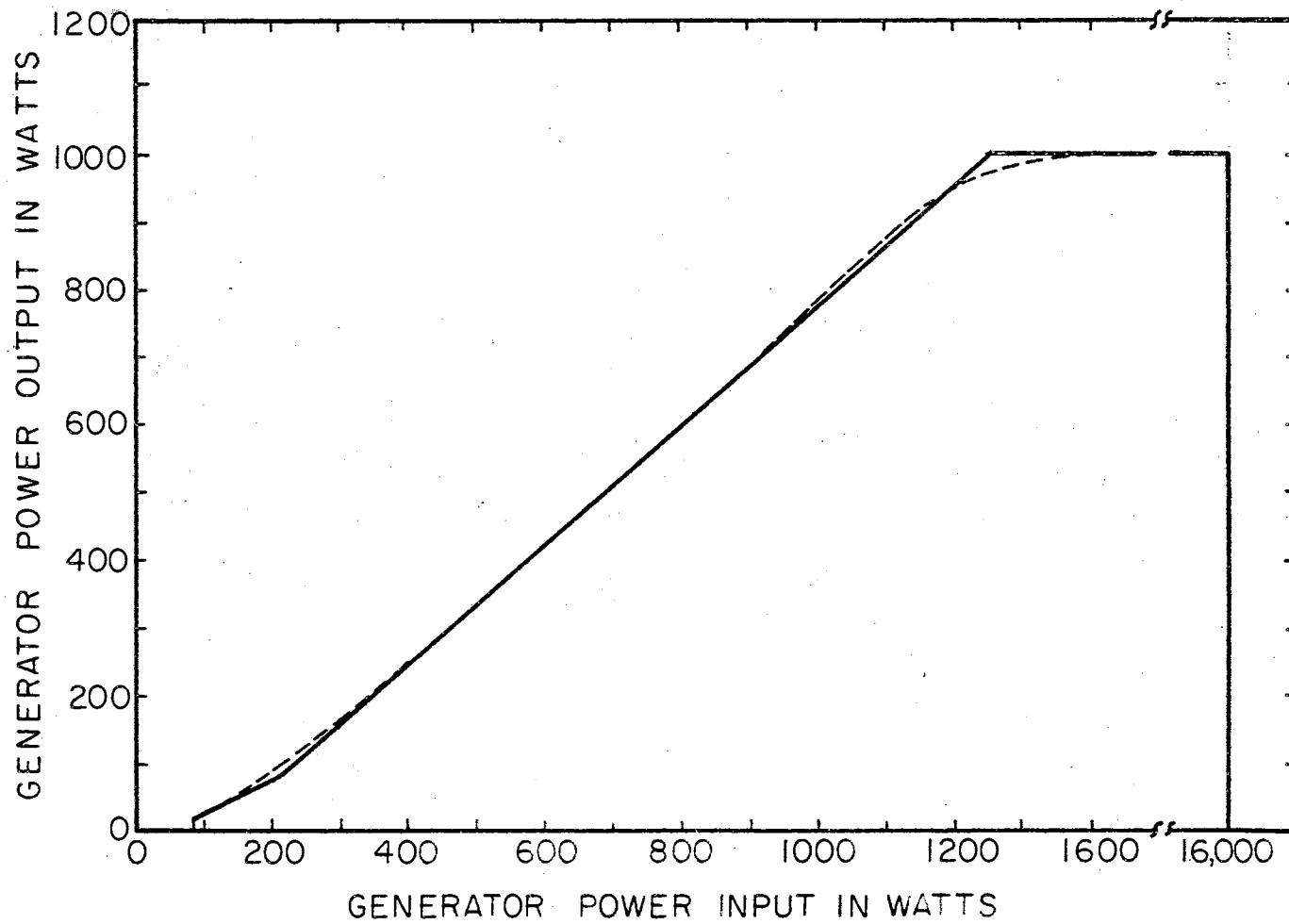
Figure 13. Normalized Generator Transfer Function Relating Electrical
Power Output to Mechanical Power Input

under pressure providing increasing pressure in the pressure vessel until a relief valve is opened or the output is switched to another container. This characteristic of the electrolysis cell allows high pressure storage without the use of a high pressure pump. The transfer function of the electrolysis cell, Function 8, was obtained from the curves resulting from Allison's (37) work by assuming a device with a current density of 600 amperes per square foot at full power. Figure 14 shows the output from the electrolysis cell versus the power into the electrolysis cell.

Cavern Storage for Gas

From the electrolysis cell the gases are piped to high pressure storage areas. The means of storage might be thick walled metal containers or deep caverns in granite or other solid rock. The metal containers are more economical for the quantities considered in this study (3). Current developments in the field of pressurized containers include coils of thin-walled tubing and also plastic tanks. The thin-walled tubing is not yet sufficiently developed for consideration economically and the plastic tanks will not operate much in excess of 1000 pounds per square inch. For these reasons the costs for metal tanks were used in the computer programs. The cost figure of 833 mils per kilowatt-hour is obtained by dividing the cost of $15.00 per cubic foot by the energy of 18 kilowatt-hours stored per cubic foot of hydrogen at 3000 psi (3).

Fixed Components

The three components whose sizes are varied in this design
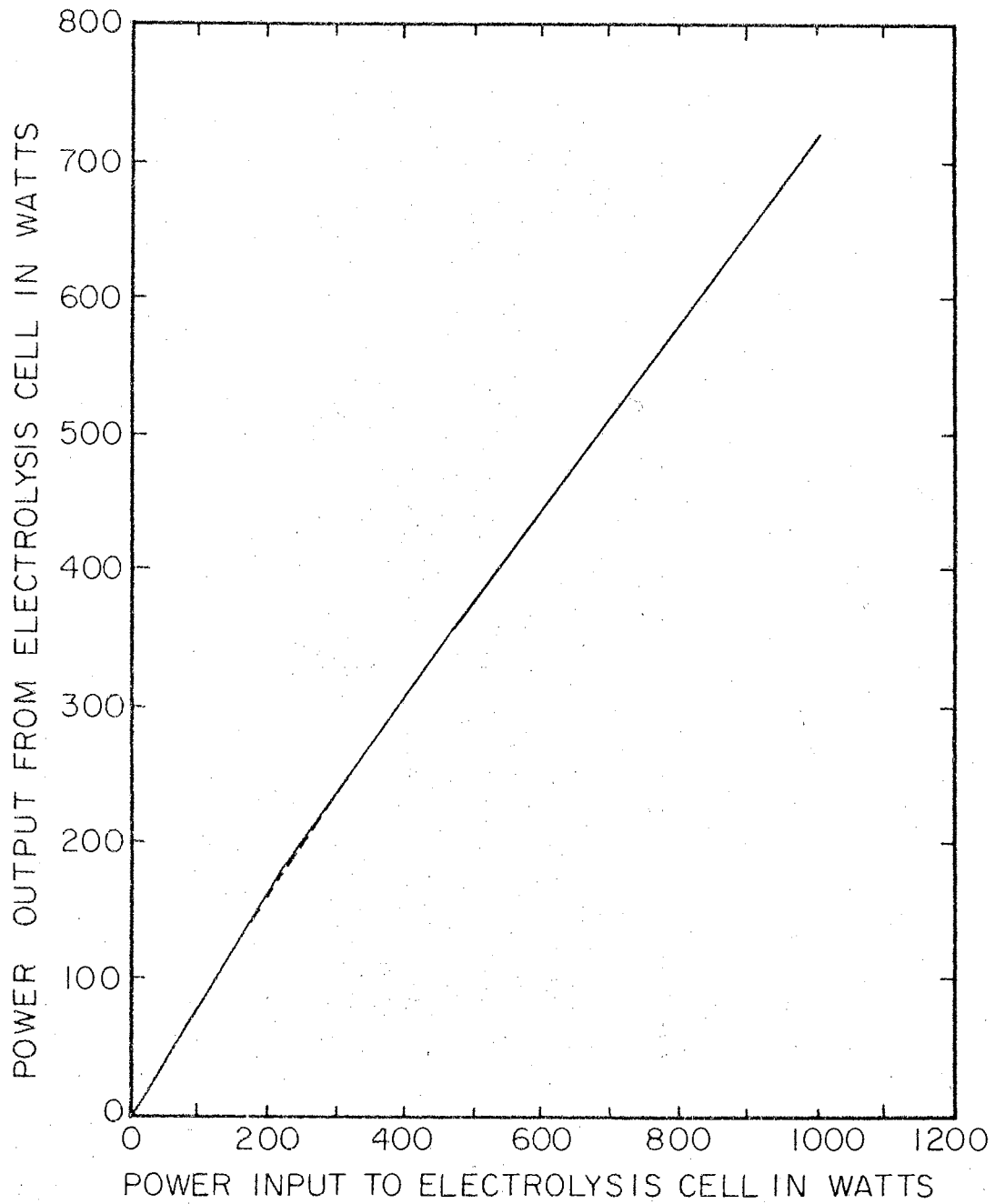
Figure 14. Normalized Electrolysis Cell Transfer
Function Relating Stored Chemical
Power Output to Electrical Power
Input

procedure are the wind intercept area, the generator-electrolysis cell combination, and the storage capacity of the energy storage tanks. The costs of various combinations of these components will be calculated in order to arrive at a design that is economically acceptable and also desirable from such other considerations as future expansion, maintenance, etc.

The fixed components are those associated with the output; they would differ somewhat depending upon which output was to be supplied by the system. The irrigation system proposed by McCollom (4) lists an engine and pump unit plus pipes and installation to cost $480. Rounding this figure off to $500 seems reasonable for the costs of the burner, blower, and ducts necessary for the drying of grain. This same figure of $500 is not unreasonable for the cost of an inverter, transformer, and transmission line for the distribution of one kilowatt of power. So, for the sake of uniformity, let the fixed costs of the output portion of the system be $500 in each case.

Limits on Component Sizes and Most Promising Regions

In a design problem one generally desires to know what the boundaries for the variables are, if any exist. Also, within the range of permissible values, one would like to know what regions offer the most promise. To this end a discussion of each variable is in order.

The first variable, the capacity of the energy storage unit, is to be considered from two viewpoints. The first viewpoint is that of supplying vital services during a period of absolute calm winds or during a period of unexpected breakdown of the input part of the system. For irrigation purposes a capacity of zero would be a perfectly

legitimate starting place since a two or three day delay in irrigation would not generally be vital. On the other hand, if the system supplied a hospital, the humanitarian considerations would demand an adequate reserve for the continued operation of the critical equipment. Even for a small load such as a one-family farm home there can be some loads such as a deep-freezer whose continued operation would be important. Thus, the type of load will determine the minimum acceptable value of the energy storage capacity.

For the example situation assume that the minimum load of 250 watts represents critical equipment and that the time period specified for this reserve is four days. This results in a storage capacity of not less than 24 kilowatt-hours. This figure not only represents the minimum value to be considered for the storage capacity, it also represents the minimum storage content that should ever occur in a properly designed system since it represents emergency reserve.

The second viewpoint is strictly from consideration of cost. What is the minimum size that will meet the specifications? From this viewpoint the obvious conclusion is that one would begin the optimization search with the smallest values allowed by the previous considerations.

The size of the generator-electrolysis cell combination is the second variable to be considered. There is an absolute minimum to the size of this combination. This minimum is obtained by assuming that the storage capacity is as large as needed to absorb any fluctuations in load and that the propeller is as large as needed to keep the generator running at maximum capacity all of the time. Refer to Figure 10 and note that B1, B2, and B3 are fixed, known nonlinear functions

which are combined into one output transfer function. Whatever energy

is demanded by the load is obtained from storage through this output

transfer function. At any instant

$$s_d = \frac{l_d}{n_o}$$

where

s_d = instantaneous demand from storage, watts,

l_d = instantaneous load demand, watts,   (5.2)

and

n_o = output transfer efficiency corresponding to l_d.

Since the output transfer efficiency is a nonlinear function of magni-

tude, the program of Appendix C is used to reflect each of the hourly

demands from the load back to the storage and sum these to obtain total

storage output for the year. For the example case the total yearly de-

mand from storage is 5,883,529 watt-hours. Under the assumption that

the storage is as large as needed, no energy is discarded from storage

because of lack of capacity. Therefore,

$$S_i = S_o$$

where

S_i = total energy going into storage during
      the year, watt-hours   (5.3)

and

S_o = total energy taken from storage during
      the year, watt-hours.

Refer to Figure 10 and note that the storage input energy comes from

the electrolysis cell. Under the assumption that the generator-elec-

trolysis cell is being driven at full capacity all of the time, the

electrolysis cell efficiency is 72% according to Figure 14. In order

for the electrolysis cell to deliver 5,883,528 watt-hours of energy, it

must receive 8,171,568 watt-hours of energy according to the equation

$$E_{ei} = \frac{E_{eo}}{\bar{\eta}_e}$$

where

E_{ei} = total yearly electrolysis cell input energy,

watt-hours,   (5.4)

E_{eo} = total yearly electrolysis cell output energy,

watt-hours,

and

$\bar{\eta}_e$ = yearly electrolysis cell efficiency.

Figure 10 shows that the generator supplies the input to the electroly-

sis cell, therefore, the output from the generator must be 8,171,568

watt-hours of energy for the year. Since there are 8760 hours in a

year and the generator is running at full capacity all of the time, the

generator rating is

$$P_{go} = \frac{E_{ei}}{8760}$$

where

P_{go} = generator output power rating, watts

(5.5)

and

E_{ei} = total yearly electrolysis cell input energy,

watt-hours.

For the example case this rating is 933 watts. Because of the periods

of calm or near clam when the winds are below about 5 knots, this

figure of 933 watts should be adjusted upward to about 1000 watts as a

practical minimum. Although this minimum generator size was obtained

by assuming an impractically large propeller, the value of 1000 watts

is useful as a minimum limit for the grid-search technique.

The third variable, the wind intercept area, is governed by the propeller length according to the expression for the area of a circle $\pi d^2/4$. Thus, in selecting a wind intercept area, one is actually specifying the propeller length. The minimum size for the wind intercept area is again determined by assuming that the other two variables, the generator and storage sizes, are as large as necessary. The first step in determinimg the minimum wind intercept area is to determine the necessary average propeller output. Since the average propeller output is the average generator input, this quantity may be approximated by dividing the average generator output by an average generator efficiency. Becuase the generator was assumed to be operating at full capacity at all times in Equation 5.5, the 933 watts calculated there, which was a constant output, now becomes the average generator output. For an assumed average generator efficiency of 50%,

$$\bar{P}_{po} = \bar{P}_{gi} = \frac{\bar{P}_{go}}{\bar{\eta}_g} = \frac{933}{0.5} = 1866 \text{ watts}$$

where

(5.6)

$\bar{P}_{po}$ = average propeller output, watts,

$\bar{P}_{gi}$ = average generator input, watts,

$\bar{P}_{go}$ = average generator output, watts,

and

$\bar{\eta}_g$ = average generator efficiency.

An average propeller efficiency of 35% is used to refer the average propeller output through the propeller to the theoretical power available in the wind. The average theoretical wind power needed is

$$\bar{P}_{wt} = \frac{\bar{P}_{po}}{\bar{\eta}_p} = \frac{1866}{0.35} = 5331 \text{ watts} \qquad (5.7)$$

where

$\bar{P}_{wt}$ = average theoretical wind power applied to the
propeller, watts,

$\bar{P}_{po}$ = average propeller output, watts,

and

$\bar{\eta}_p$ = average propeller efficiency.

An average value of 18.64 watts per square foot for theoretical wind power is obtained from Equation 5.1 if the expected value of the cube of the wind velocity is inserted. The expected value of wind velocity cubed is obtained from the approximation of the statistical equation

$$E[V^3] = \int_{V_{min}}^{V_{max}} V^3 f(V)dV \cong \sum_{k=0}^{k=36} k^3 \frac{N_k}{8760} = 2312 \text{ knots}^3$$

$$(5.8)$$

where

$E[V^3]$ = expected value of cube of wind velocity, knots^3

V_{min} = minimum wind velocity, knots,

V_{max} = maximum wind velocity, knots,

V = instantaneous wind velocity, knots,

$f(V)$ = statistical distribution of wind velocity $\cong \dfrac{N_k}{8760}$,

N_k = number of hours during the year that the
wind velocity was k knots,

and

k = hourly wind velocity (integer values), knots.

Since the wind velocity data are discrete integers, the integral may be

replaced by the approximate summation with no loss of accuracy in this case.

The necessary wind intercept area is

$$A_{wi} = \frac{\bar{P}_{wt}}{P} = \frac{5331}{18.64} = 286 \text{ ft}^2 \qquad (5.9)$$

where

A_{wi} = require wind intercept area, ft^2,

$\bar{P}_{wt}$ = average theoretical wind power applied to the propeller, watts,

and

P = power density available in the wind of wind intercept area, watts/ft^2.

This value of wind intercept area is only an approximation since approximate values were used for a number of the quantities. Also, it is applicable only for large storage capacities and generator sizes. Nevertheless, it is quite useful since it provides a starting place.

The value for the wind intercept area just estimated is a start-ing place for conditions of a large generator and a large storage. As the size of the generator is decreased, the energy contained in the higher wind velocities is lost so the propeller must be made larger in order to compensate for this loss. Likewise, as the energy storage capacity is decreased, the energy generated when the storage is full must be discarded. Again propeller size must be increased to compen-sate for this loss. Thus, the corresponding wind intercept areas will be graduated upward as either generator size or storage capacity is decreased.

The most promising regions to be investigated are of interest if computer time is to be conserved. One would expect the storage

capacity to be considerably larger than the 24 kilowatt-hours selected
as a minimum. The reason for this anticipation is the combination of
light summer winds and heavy summer loads. One would anticipate a need
for about a two-month storage supply, a 500 to 600 kilowatt-hour capa-
city, to reduce peak requirements on the other two variable components.
Likewise, about a 50% increase in generator size above minimum would
allow the total output demand to be met without the need for an ex-
tremely large propeller to utilize even the very light breezes. Simi-
larly, one would expect to increase the minimum wind area by at least
a factor of two. This increase compensates for the energy discarded
because of the limitations imposed by the realistic generator size and
storage capacity.

Reason dictates that abnormally large values for any of the three
variable components will not produce an economic minimum. For a system
passing a total of six magawatt-hours of energy through storage in a
year, one would not anticipate an energy storage requirement in excess
of one megawatt-hour to be economically desirable since both input and
output are spread over the entire year. Likewise, one would not expect
to obtain an economic minimum with an extremely large generator since,
for progressively larger generators, there comes a point at which the
propeller size must be increased just to overcome friction to start
the generator turning. Similarly, as the propeller size is progress-
ively increased, there comes a point at which it drives the generator
at full capacity for even a light breeze. Any further increase in
propeller size adds to the cost of the system but does not increase
generator output. Hence, the most productive area for search is not
expected for an unreasonably large value for any one of the three

variables.

The preceeding discussions outline lower limits for component sizes, indicate the general regions where an economic minimum can be anticipated, and give reasons for concluding that an economic minimum will not occur for unusually large values for any one of the three variables.

Selecting the Search Grid

After determining the approximate limits and area most likely to produce a minimum-cost design, the grid of Figure 15 was chosen for preliminary investigation. The values for both storage capacity and generator cover the most promising regions for these variables. The point on this grid which produced a minimum cost was the point at a storage capacity of 200,000 watt-hours and a generator size of 1800 watts. From this information the grid refinement shown in Figure 16 was selected for further investigation. This grid refinement concentrates the search in the area of the minimum-cost point resulting from the investigation of the coarse grid. The points to be investigated extend in all directions from the minimum-cost point of the coarse grid.

Selecting Initial Trial Values for Wind Intercept Area

The rough approximation for the minimum wind intercept area was calculated to be 286 square feet. Since this was calculated for a very large generator and a very large energy storage the initial trial value for the largest generator and for the largest storage on the grid was somewhat greater than this value. This was the upper right-hand
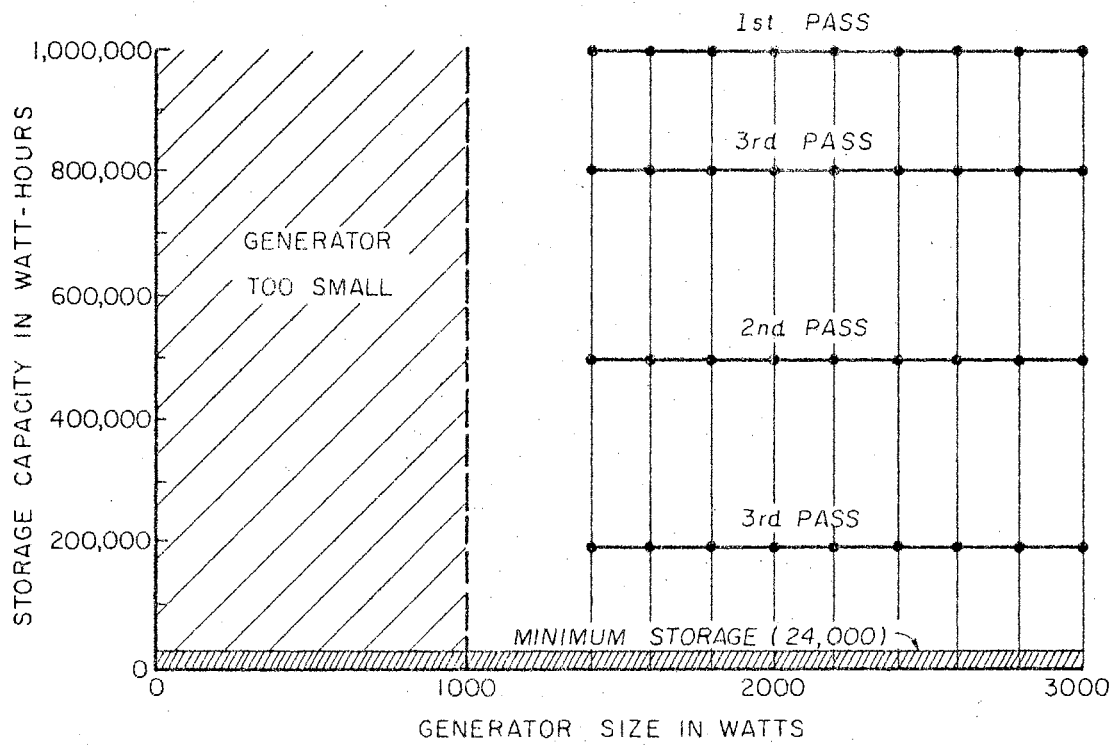
Figure 15. Initial Search Grid for Power System Components
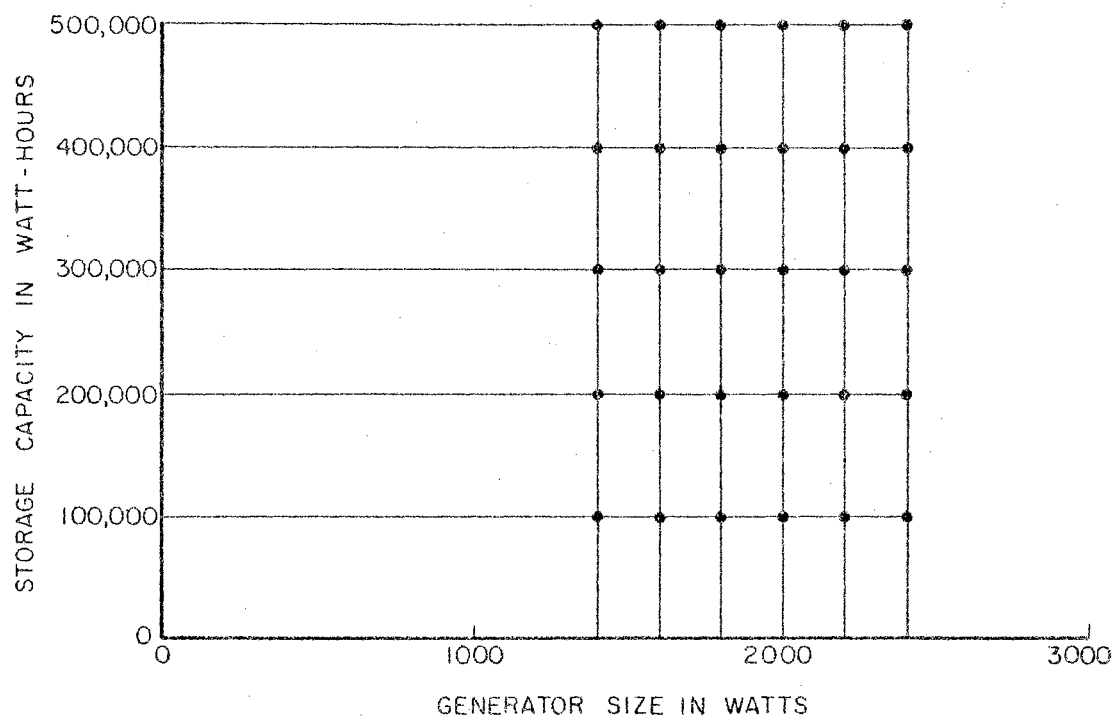
Figure 16. Refinement of Search Grid for
Power System Components

point on the search grid. Trial values were graded upward as smaller
values of either generator or storage were taken. In general the
guesses proved to be higher than needed.

Computer-Aided Study

Abbreviated Simulation

As explained previously the abbreviated simulation is used on the
many points of the search grid in order to save computer time in de-
termining the location of an approximate minimum. The abbreviated
simulation omits some details of the full-scale simulation and operates
on averaged, or compressed, data. Although this averaging reduces the
accuracy, the bias thus introduced is a predictable one so its effect
can be taken into account when interpreting the results. By using
twelve-hour averages for the wind power values and load demand values,
the number of points per simulation is only 730. The averages for the
winds were the averages of the cubes of the velocities instead of the
velocities since the power produced is proportional to the cube of the
wind velocity.

This averaging process favors the smaller generator sizes. See
Figure 17. Note that the first seven hours have considerably smaller
velocities than the remaining five hours in the interval N through
N + 12. Assume that the dashed line represents the wind velocity which
will produce maximum output from the generator. The first seven hours
will have outputs less than maximum whereas the last five would pro-
duce maximum output, but no more than maximum. When these twelve
readings are cubed and averaged, the result could easily be enough to
produce maximum output. Thus the generator would seem to produce
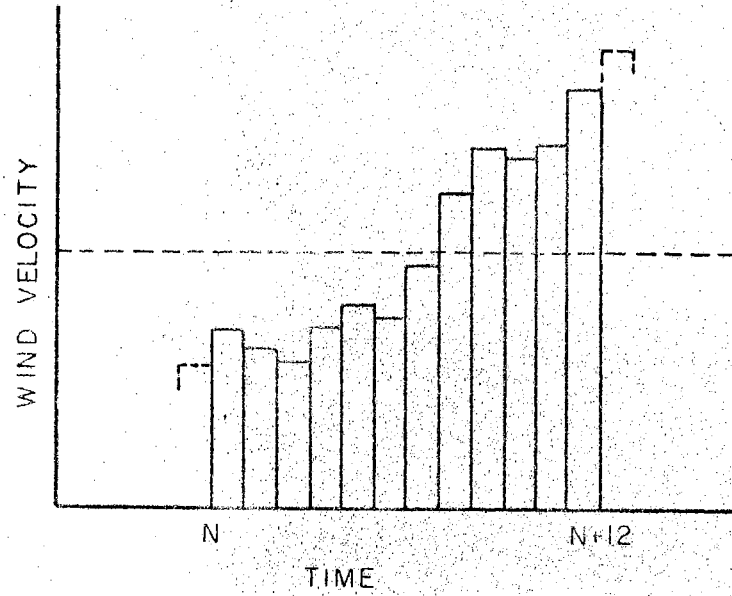
Figure 17. An Example Twelve-Hour Period to Show the Effect of Averaging

$\dfrac{\text{COST}}{\dfrac{\text{WIND}}{\text{AREA}}}$

STORAGE CAPACITY IN WATT-HOURS	1400	1600	1800	2000	2200	2400
500K	1258 / 402	1209 / 347	1200 / 318	1214 / 305	1238 / 298	1267 / 295
400K	1269 / 465	1180 / 383	1160 / 347	1164 / 327	1185 / 318	1211 / 313
300K	1316 / 552	1167 / 430	1135 / 386	1130 / 360	1146 / 348	1171 / 342
200K	1305 / 600	1179 / 493	1145 / 448	1151 / 429	1165 / 416	1190 / 410
100K	2137 / 1210	1586 / 820	1438 / 699	1382 / 639	1364 / 604	1377 / 590

GENERATOR SIZE IN WATTS

Figure 18. Search Grid Showing Results of Abbreviated Simulation of Example Power System

maximum output for the entire twelve-hour period. This effect is brought about by the fact that the averaging process used the peak powers of the larger values to fill in the troughs whereas in practice these peaks would have been discarded by a generator of small capacity. As the size of the generator is increased, the peak energy is utilized more so the averaging process more nearly represents the true situation. Therefore, this design approach is biased in favor of the smaller generator sizes by making them seem to produce more output than they actually would. This bias will be kept in mind when interpreting the results and then will be reduced by the full-scale simulation which will be performed on a few promising combinations.

This program for the abbreviated simulation is explained in detail in Appendix D for persons who are familiar with GPSS. These next few paragraphs contain an overview of the use of the program along with some causes that influenced arbitrary choices.

The plan of attack for the program is to determine the size of wind intercept area needed to drive a given combination of generator size and storage capacity as are dictated by the program control cards.

Refer back to the grid in Figure 15 to visualize the search pattern used. The first pass with the program is shown for a storage capacity of 1,000,000 watt-hours. This value was chosen as a starting place since it is well beyond the most promising region of 500,000 or 600,000 watt-hours predicted previously. The first generator size tried was 1400 watts since the minimum was predicted at about 1600 watts and it is desirable to bracket the minimum when possible. A simulation for one year was performed with a trial wind intercept area,

a rough extrapolation from the limiting area previously calculated.
The program then adjusts the area depending upon the minimum storage
content and repeats the simulation. The program then shifts to the
next larger generator size, 1600 watts, along with its trial wind
intercept area. The two simulations are run as before and then the
program goes to the next set of values for generator size and trial
wind intercept area.

Since data are printed out at the end of each simulation, the
programmer can evaluate the effectiveness of the correction on wind
intercept area. After this pair of simulation runs has been perform-
ed for each generator size at a given storage capacity level, the
programmer extrapolates the correction to obtain a new trial wind
intercept area for each generator size. The program is run as before;
a simulation is followed by a correction in wind area and a second
simulation for each generator size. The results from the second run
usually showed a satsifactory minimum storage content; an acceptable
minimum was set as being greater than 24,000 but less than 30,000
watt-hours of energy. For those points outside this range, the program
was run a third time. There is a good reason for not attempting to
build into the program an exact correction. First, the arithmetic
manipulations available in GPSS are crude and time consuming in com-
parison to other computer languages. Second, the large number of non-
linearities in the system operation would force any truly effective
correction to be quite sophisticated and complex. For these reasons
the choice was made to let the program make a rough correction and
then let the programmer extrapolate that correction.

The grid in Figure 15 is bisected by a second set of points at

the storage capacity of 500,000 watt-hours. Again various generator

sizes were selected and the corresponding wind intercept area was de-

termined. When the results of this second set of points showed the

costs to be less than for 1,000,000 watt-hours of storage, the investi-

gation was continued with a storage capacity of 200,000 watt-hours and

800,000 watt-hours. An inspection of the data from this search grid

revealed the minimum cost point for this grid to be at 200,000 watt-

hours of storage and a generator size of 1800 watts. Thus, the grid

of Figure 16 was selected for investigation and the results are as

shown in Figure 18.

This table of results shown in Figure 18 is important information

for the design parameters selected. However, further refinement of

the calculations at the chosen points is needed to determine the exact

value of the wind intercept area. This refinement is provided through

a full-scale simulation.

Selection of Most Promising Points

Inspection of the data recorded in Figure 18 is the first step in

the selection of the most promising points which will be chosen for a

full-scale simulation. A general inspection reveals that the minimum

cost is associated with the point near the center that is outlined

heavily. However, the minimum is not at all well defined. Therefore,

other points should be considered if there are secondary reasons for

choosing any point other than the point at which minimum cost occurs.

For reasons given below the point near the lower left-hand corner that

is heavily outlined was also chosen for a full-scale simulation.

Some secondary considerations are things such as the more popular

generator sizes making replacement parts more readily available or choosing a design which will most readily lend itself to expansion as the needs grow. In line with this latter reason, the choice should incorporate the largest practical propeller size and the smallest practical energy storage. These choices are desirable because of the relative difficulty of changing the sizes of the three parameters after the equipment has been installed. A larger propeller would require a larger mounting tower with a stronger system of guy wires. This change would require extensive rebuilding. Next in the order of difficulty is a change in the generator size. If the generator were replaced, the energy coupling system, belts and pulleys or gears, may need changing and the mounting holes would probably need to be re-drilled. If, instead of replacement, another generator is added, both energy coupling and mounting are involved.

The easiest parameter of all to increase is the storage capacity. All that is needed here is the replacing of an ell by a tee connection at some point in the gas storage feed line plus the installation of the additional storage tank with its feed line. For these reasons the point at a generator size of 1600 watts and a storage capacity of 100,000 watt-hours was chosen for a full-scale simulation along with the minimum-cost point at a 2000 watt generator and 300,000 watt-hours of storage capacity.

Full-Scale Simulation

The program which performs a full-scale simulation of the operation of the system for one year is the final computer design tool. This program is explained in detail in Appendix E. It operates with a

fine degree of realism. The transfer functions have been represented quite closely by straight-line approximations. Actual data for each hour are used as inputs for both wind velocity and load. Even wind gusts are simulated ten times each hour.

The purpose of this final, more elaborate simulation is to approximate the actual system operation as nearly as is practical in order to obtain more nearly correct values for the system components. This step is needed since the answers given in Figure 18 are a good indication of the relative costs for each combination of components but the actual component choice must be refined before a confident choice can be made.

The first point selected for a full-scale simulation was the minimum-cost point of Figure 18 which was composed of a storage of 300,000 watt-hours, a 2000 watt generator, and a wind intercept area of 360 square feet. A full-scale simulation of the system using these components demonstrates that the wind intercept area is inadequate. This inadequacy was predicted in the section of Abbreviated Simulation which used Figure 17 to demonstrate how the averaging effect causes the smaller generators to appear to be supplying more power than they actually are. Subsequent full-scale simulations revealed that a wind intercept area of 400 square feet was needed. The data for this point, point 1, are entered in Table III. The revised wind intercept area is used; cost reflects revised wind intercept area and fixed costs of $500.

The importance of the full-scale simulation is undeniably established by the second point chosen from the grid of Figure 18 for full-scale simulation. This point appears at a storage capacity of 100,000 watt-hours and a 1600 watt generator. Various sizes of wind intercept

TABLE III

COMPARISON OF RESULTS OF FULL-SCALE SIMULATION

	Generator Size in Watts	Storage Capacity in Watt-Hours	Wind Intercept Area in Square Feet	Propeller Diameter in Feet	Cost in Dollars
Point 1	2,000	300,000	400	23	1690
Point 2	1,600	100,000	Impossible	--	----
Point 3	1,800	100,000	1080	37	2510

area were used up to and including 2500 square feet but none would
supply enough energy to maintain the minimum amount of energy in stor-
age.

The failure of the second point to provide the necessary energy
led to the choice of a third point for full-scale simulation. Two
choices are available; either the storage capacity may be increased
or the generator size may be increased. Because the storage capacity
will be easier to increase after installation, the design decision was
made to increase the generator size of the original design effort.
Thus, the third point for full-scale simulation appears at a storage
capacity of 100,000 watt hours and a generator size of 1800 watts in
Figure 18. The full-scale simulations indicated a need for a wind
intercept area of 1080 square feet. These data are entered for point
3 in Table III.

Final Selection of Components

The final selection of components is based in part upon the re-
sults of the computer simulations, in part upon the secondary consider-
ations involved, but also using the experience and judgment of the
engineer to decide how much weight to give each of the bits of informa-
tion that he has. Table III is a comparison of the computed data for
the points selected for full-scale simulation. The second point is
disqualified so there remain the first and the third points to be
compared.

The first point has a cost that is approximately two-thirds that
of the third so it has a considerable advantage here. Replacement
parts and maintenance would not favor one over the other. The

possibilities for expansion are considerably in favor of the third
point. Based upon the data in Figure 18 for large storage capacity
and large generator size and upon the rough approximation of 286 square
feet for a minimum wind intercept area, point one is limited to about
30% expansion capabilities for even very large generator sizes and
storage capacities. On the other hand, point three can have its capa-
city doubled by the addition of $250 worth of storage capacity and has
an ultimate capability of approximately four times the design capacity
for an expenditure of less than $1000 in addition to the initial $2510.
In view of the rapid technical advances in all parts of the world, the
engineer would anticipate that the demands upon the power system could
reasonably be expected to exceed the expansion capabilities of the
first point so the third point would be selected as the recommended
design point.

The actual phsyical components represented by the variables
would be chosen from commercially available units as follows. The
generator and electrolysis cell would each have a design rating of
1800 watts. The energy storage unit would be two standard 3.2 cubic-
feet units with a total energy storage capacity of 115,200 watt-hours
based on a storage capability of 18,000 watt-hours per cubic foot of
hydrogen at 3000 pounds per square inch. The wind intercept area
results in a propeller slightly longer than 37 feet in diameter so the
recommended unit would be a propeller 40 feet in diameter atop a 60-
foot tower.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Design Procedure

The objective of developing a design procedure for power systems
using unconventional energy sources and energy storage has been met.
In fact, the design technique is more general, since the resulting
procedure can be applied to any nonlinear system which can be repre-
sented by the block diagram of Figure 5. This procedure, which is
explained in Chapter IV and diagrammed in Figure 6, points out the
interplay between engineer and computer in this computer-aided design.
The invaluable contribution of the computer in simulating the non-
linearities with ease and speed should be stressed. Conversely, the
solutuions obtained from the computer must not be the sole source of
information upon which the final choices are made. The engineer must
weigh all the information that he has relying on his engineering
judgment for the final choice of design components.

Computer Programs

The computer programs developed to be used in conjunction with
the computer aided design procedure are explained in the appendices.
The ease of programming GPSS and its adaptability to varying problems
are well known. A significant contribution has been accomplished using
GPSS through the sequences of control cards at the end of the program

to iterate the simulations within the computer. This provides conver-
gence toward a solution at a given point, proceeds to another point,
converges toward a solution there, and then proceeds to another point,
etc. until a search grid has been covered. Therefore, the computer-
ized grid-search technique that is common in hybrid computers can now
be used with GPSS simulations as well, thus affording a much more
powerful tool for computer-aided design.

Future Investigations

Combined Wind and Solar Systems

The recent developments in solar cells are expected to bring about
a reduction in their cost. If this reduction in cost does materialize
there should be a study made of a power system using a combination of
both wind and sunlight for unconventional sources of energy since these
two sources complement each other on a yearly basis. The additional
programming necessary for this study has been illustrated in Appendix
F.

Larger Systems

For larger systems where increased efficiency is of major impor-
tance a direct path from source to load should be incorporated into
the system model. These systems may be studied by using a simulation
program developed by the author and presented at the Second Conference
on Applications of Simulation (6).

Self-Adjusting, Variable-Pitch Propeller

Early in this study the question arose regarding the choice

between a propeller and a squirrel case rotor as a wind intercept device. Investigation at Oklahoma State University clearly showed the superiority of the propeller. However, one weakness of the propeller is its inability to extract an appreciable amount of energy from a wind gust. Appendix G presents a suggested design for a self-adjusting, variable-pitch propeller which should be able to respond rapidly to varying wind velocities. The simplicity of the design should make the propeller relatively inexpensive. Also, a reversal of the direction of the torque from the spring would allow this principle to be applied to light aircraft propellers. The development of this self-adjusting, variable-pitch propeller is recommended.

SELECTED BIBLIOGRAPHY

1. Energy Storage (Key to Our Economic Future). The Office of Engi-
        neering Research, Oklahoma State University, Stillwater, Okla-
        homa, 1963.

2. Proceedings of the United Nations Conference on New Sources of
        Energy, Rome, 21-31, Aug., 1961, Vols. 1-7, United Nations,
        New York (1964).

3. Proceedings of the Conference on Energy Conversion and Storage, The
        Office of Engineering Research, Oklahoma State University,
        Stillwater, Oklahoma, 1963.

4. Research Proposal, Developing Unconventional Energy Sources for use
        in Developing Countries. The Office of Engineering Research,
        Oklahoma State University, Stillwater, Oklahoma (1967).

5. McCollom, K. A. "Use of Energy Storage with Unconventional Energy
        Sources to Aid Developing Countries." Advances in Energy
        Conversion Engineering, From the Intersociety Energy Conver-
        sion Conference Held at Miami Beach, Florida, August, 1967,
        The American Society of Mechanical Engineers, New York, 1967.

6. Easter, B. H. "An Energy Storage System." Digest of the Second
        Conference on Applications of Simulation, Institute of Elec-
        trical and Electronic Engineers, New York, 1968.

7. Betz, A. "Windmills in the Light of Modern Research." Tech. Memo.
        No. 474., National Advisory Committee for Aeronautics (1927).

8. Putnam, P. C. Power From the Wind. New York: Van Nostrand, 1948.

9. Golding, E. W. The Generation of Electricity by Wind Power. New
        York: Philosophical Library, Inc., 1956.

10. Energy Conversion and Storage Research. Annual Report for the year
        ending August 31, 1967, School of Electrical Engineering,
        Oklahoma State University, Stillwater, Oklahoma (1967).

11. Energy Conversion and Storage Research. Annual Report for the year
        ending August 31, 1968, School of Electrical Engineering,
        Oklahoma State University, Stillwater, Oklahoma (1968).

12. Bruckner, Arthur, II, "A System for the Economic Analysis of Bal-
        anced Energy Conversion and Storage Systems." (unpub. Ph.D.
        thesis, Oklahoma State University, 1967).

13. Gibson, L. A. "Wind Analysis in Relation to the Development of Wind Power." (unpub. Ph.D. thesis, Oklahoma State University, 1969).

14. McLeod, J. Simulation. San Diego: Simulation Councils, Inc. IV (Editorial, February, 1968).

15. McLeod, J. "Simulation is Wha-a-at?" Simulation, Vol. 1 (1963).

16. McLeod, J. "Manned Spacecraft Simulation." Simulation, Vol. 1 (1963).

17. Jackson, A. S. Analog Computation. New York: McGraw-Hill, 1960.

18. Fifer, S. Analogue Computation, Vol. 1. New York: McGraw-Hill, 1961.

19. American Federation of Information Processing Societies Conference Proceedings, Vol. 31. Washington: Thompson Books, 1967.

20. Karplus, W. J. Analog Simulation, Solution of Field Problems. New York: McGraw-Hill, 1958.

21. Korn, G. A., and T. M. Korn. Electronic Analog Computers (D-C Analog Computers), 2nd ed. New York: McGraw-Hill, 1956.

22. Smith, G. W., and R. C. Wood. Principles of Analog Computation. New York: McGraw-Hill, 1959.

23. Johnson, C. L. Analog Computer Techniques. New York: McGraw-Hill, 1956.

24. Selfridge, R. G. "Coding a General-Purpose Digital Computer to Operate as a Differential Analyzer." Proceedings of the 1955 Western Joint Computer Conference, Institute of Radio Engineers, New York, 1955.

25. Linebarger, R. N., and R. D. Brennan. "Digital Simulation for Control System Design." Presented at the 6th Joint Automatic Control Conference, Troy, New York, 22-25, June, 1965, IBM Corporation, San Jose, California (1965).

26. System/360 Continuous System Modeling Program (360A-CX-16X) Application Description. User's Manual H20-0240-2. White Plains, New York: IBM Corporation, 1968.

27. Engineering Research Associates, Inc. High Speed Computing Devices. New York: McGraw-Hill, 1950.

28. Glinski, G. "Digital and Analog Computers, a Unified Approach." Lecture delivered to National Research Council Science Association, Ottawa, Nov. 17, 1954.

29. McLeod, J. H., and R. M. Leger. "Combined Analog and Digital Systems - Why, When, and How." Instruments and Automation, Vol. 30 (1957), 1126-1130.

30. Hurney, P. A., Jr. "Combined Analogue and Digital Computing Techniques for the Solution of Differential Equations." Proceedings of the Western Joint Computer Conference, New York, American Institute of Electrical Engineers (1956), 64.

31. Howe, R. M. "Hybrid Computers." Lecture delivered at Seminars in Modern System Theory, Center for Systems Science, Oklahoma State University, Stillwater, Oklahoma, March 7, 1969.

32. "Analog and Hybrid Computers in Education: A Panel Session." American Federation of Information Processing Societies Conference Proceedings, Vol. 30, Washington: Thompson Books, 1967.

33. Digest of the Second Conference on Applications of Simulation. New York: Institute of Electrical and Electronic Engineers, 1968.

34. General Purpose Simulation System/360 User's Manual H20-0326-2. White Plains, New York: IBM Corporation, 1968.

35. Kiviat, P. J., and R. Villanueva. The SIMSCRIPT II Programming Language. R-460-PR. Santa Monica: The RAND Corporation, 1968.

36. IBM System/360 Fortran IV Language, C28-6515. White Plains, New York: IBM Corporation, 1968.

37. Energy Conversion and Storage Research. Quarterly Report for the quarter ending March 31, 1967, School of Electrical Engineering, Oklahoma State University, Stillwater, Oklahoma (1967).

38. Evans, G. E. "Electrochemical Energy Storage for Intermittent Power Sources." Proceedings of the United Nations Conference on New Sources of Energy, Rome, 21-31, August., 1961, Vol. 1, United Nations, New York (1964).

39. Merchant, D. A. "Stochastic Model of Wind Gusts." (unpub. Ph.D. thesis, Stanford University, 1965).

APPENDIX A

PHYSICAL PROPERTIES TO BE SIMULATED

Pertinent System Characteristics

In any simulation the purpose is to study system behavior by building analogs which perform in the same manner as the system components. These analogs may be either physical elements or segments of a computer program. By interconnecting these analogs properly, a system is simulated. The programmer must exercise care in determining which system characteristics are pertinent.

Wind Velocity and Solar Intensity

Figure 19 is a plot of the hourly wind velocity readings at Will Rogers Airport in Oklahoma City for January of 1962. While the solar energy would exhibit fluctuations of much lower frequencies, it too, is unpredictable. Each of these phenomena is characterized by a random fluctuation about some cyclic components. The solar intensity obviously has a daily cycle and a yearly cycle. The wind velocity has a yearly cicly and a four-day cycle caused by weather fronts moving across the nation. Therefore, an acceptable simulation should have an input composed of these cyclic components and a superimposed random fluctuation.

According to a report from Stanford University the gustiness of the wind depends upon the surrounding obstructions and may be
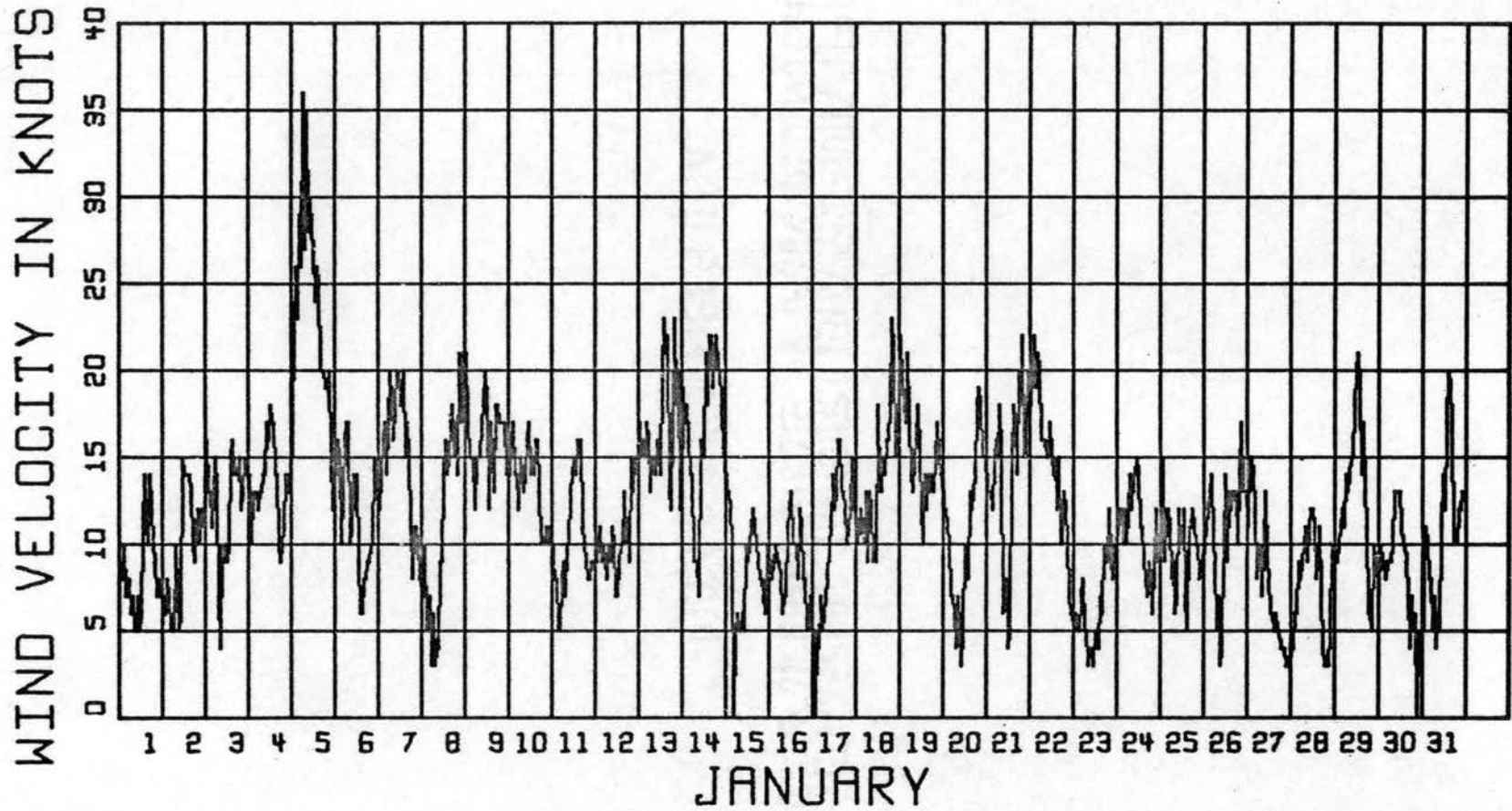
Figure 19. Wind Velocity Data for January 1962 at Will Rogers Airport in Oklahoma City

approximated within 2% by a normal distribution (39). Thus, one may

take smoothed data and reinsert the wind gusts by using a random num-

ber generator and an error function curve in the manner illustrated by

Figure 20 . The error function is used since it is the distribution

function for the normal curve.

Component Transfer Characteristics

The generator output varies as the input power varies but the

function relating the two is nonlinear. A GPSS function, see Figure 21,

is readily adapted to approximating this nonlinear function by straight

line segments. The relationship between input and output also varies

during gusts because of the finite time needed for the wind-intercept

device and generator to respond. Figure 22 shows the usable wind

velocity increase during a short gust.

Storage

After the electricity is used through electrolysis to produce

gases from water the gases are stored in high-pressure tanks. The GPSS

entity of Storage seems to be ideally suited to this simulation but it

is not. During design simulations one may easily guess a value of

wind intercept area that is too small. The results are a negative

content of Storage; a condition which causes the simulation to abort.

A Savevalue may be used with equal ease without the problem of main-

taining a positive value of energy stored at all times. For this

reason a Savevalue was used to simulate the storage. Because the

present simulation is based on 0.1 hour intervals, the output power

from the electrolysis cell is divided by ten to obtain the
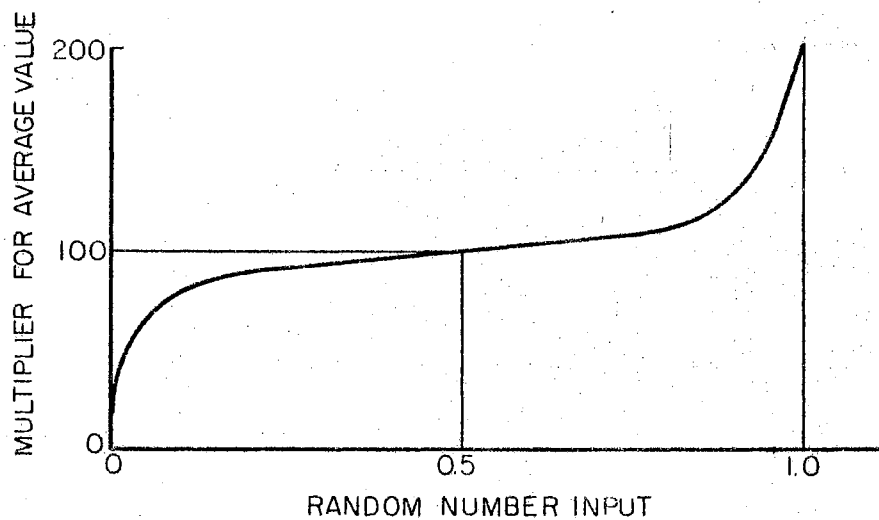
Figure 20. Wind Gust Simulation Curve Obtained
From Error Function
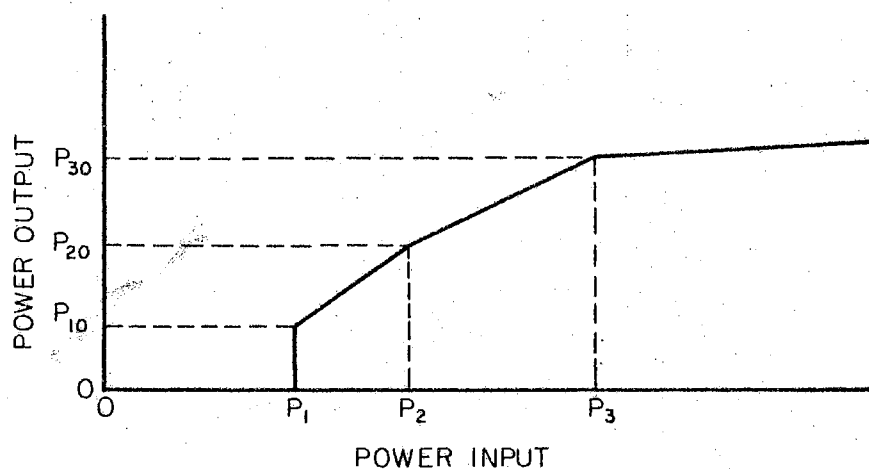
Figure 21. Example Straight-Line Approximation to
a Generator Transfer Function
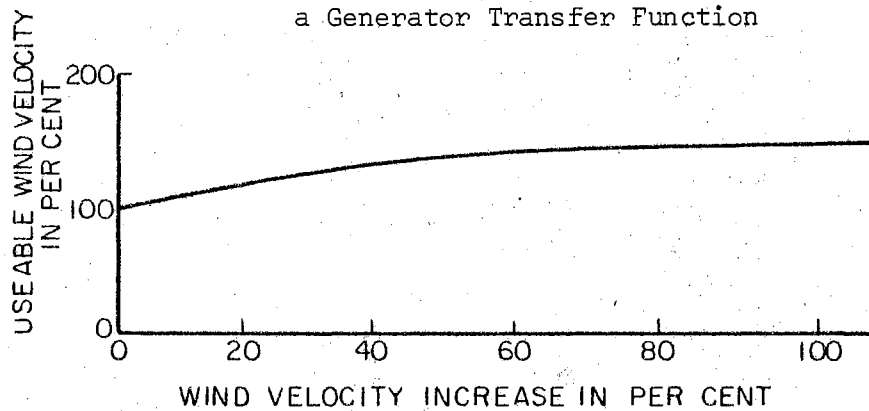
Figure 22. Effective Wind Velocity During a Gust as a
Function of Actual Wind Velocity During
the Gust

corresponding amount of energy in watt-hours. The resulting quantity is then entered into the Savevalue to represent the energy in the stored gas.

Energy leakage (gas leakage) from the tanks is simulated by removing units of energy periodically from storage. The number of units removed is a function of the total storage, i.e. the pressure in the tank. In using this program to simulate a water pump-back reservoir for energy storage the leakage would represent that water that evaporates or seeps into the surrounding soil.

Reconversion Device Characteristics

At this point the physical problems diverge but the simulation techniques do not. The reconversion characteristic functions for a fuel cell and a steam turbogenerator will differ but the result in each case will be electrical energy for some electrical load. The simulation pattern for the two cases is the same. The pattern has three parts:

1. A reconversion state wherein the stored energy is converted to some other form such as electrical, mechanical, or heat;

2. There may or may not be a transmission from point of reconversion to point of use;

3. Again there may or may not be a transformation needed at the point of use, such as a rectifier or transformer for electrical power or a gearing up or down for mechanical power.

In a developing country one of the important agricultural uses for wind-powered energy is the proper drying of grain. For this case the load would require that the energy be converted to heat so the

direct path would include the transfer function of a heating element while the reconversion device from storage would probably be a burner.

Details of Simulation of Wind Gusts and Component Transfer Characteristics

Wind Gusts

The cyclic component of the wind velocity is obtained by using actual hourly readings as raw input data. These data are modified randomly by the use of a random number generator to select a multiplier from the error function curve as shown in Figure 20. The standard deviation of the curve must correspond to the terrain surrounding the site of the wind-powered generator. In the simulation a random number is generated and used as the abscissa of this curve. The corresponding ordinate is computed and multiplied by the average velocity for this time period. This technique for simulating wind gusts is necessary for two reasons. The first is the limitation of space available in the somputer for storing wind data. The second reason is the availability of vast amounts of data from U. S. Government weather stations in the form of hourly readings. While each reading is actually the average for a one minute period each hour, these readings may be used as the hourly averages without significant error if the simulation covers a sufficiently long period of time. Gibson (13) has shown experimentally that a two-month period is long enough.

Component Transfer Characteristics

In the simulation Figures 22 and 21 are used by first determining whether there has been an increase or decrease in wind velocity from

its average value. If the velocity remains the same or decreases, the system can respond to the full velocity so the instantaneous velocity is valid as the usable velocity. If the velocity increases, the curve of Figure 22 determines the usable velocity as a percent of the average velocity. This percent is multiplied by the average velocity to produce the useable velocity. In either case the usable velocity is cubed, divided by a million to remove the percent factor, and applied to Figure 21 as the absicissa. The power output from the generator is the corresponding ordinate value.

APPENDIX B

FORTRAN PROGRAM FOR COMPRESSING DATA

There are 8760 hours in a year and the wind velocity data from

Will Rogers Airport in Oklahoma City as well as the load demand from

Public Service Company of Oklahoma lists a value for each hour in the

year. For reasons listed in Chapter IV there is a need for compressing

the data by averaging successive 12-hour intervals of data.

The averaging process for the load demand is simply a matter of

adding 12 values and then dividing by 12. For this data compression is

accomplished as shown in Figure 23 by reading the values into memory as

a matrix, A, adding successive groups of 12 values, dividing by 12,

storing the results as a matrix, B., and punching out B on cards with

six points per card. The format of six points per card is fixed by the

list function requirements of GPSS III, the language for which the

data were originally prepared. The output cards are numbered in the

last three columns for sorting purposes or reference purposes in case

only a part of the data is needed.

There were 8784 points read into the computer memory instead of

the expected 8760. If 8760 points were used, the resulting 730 points

of 12-hour averages would fill 121 cards with four points left over.

This situation would require special directions for punching the last

card. However, if 366 days are assumed by repeating the first day's

data at the end of the 8760 points, 8784 points go into the computer

87

```
C  PROGRAM FOR REDUCING THE NUMBER OF DATA POINTS
C  AVERAGES FOR 12-HOUR INTERVALS
       DIMENSION A(9600),B(800)
     1 FORMAT (6F12.1)
     2 FORMAT (2I4)
     3 FORMAT (6F12.5X,I3)
       READ (5,2)M,N
       READ (5,1) (A(I),I=1,M)
       L=M/12
       DO 500 I=1,L
       SUM=A(12*I-11)+A(12*I-10)+A(12*I-9)+A(12*I-8)+A(12*I-7)+A(12*I-6)+
      2A(12*I-5)+A(12*I-4)+A(12*I-3)+A(12*I-2)+A(12*I-1)+A(12*I)
   500 B(I)=SUM/12.
       L=M/72
       K=N
       DO 900 I=1,L
       K=K+1
   900 WRITE (7,3) B(6*I-5),B(6*I-4),B(6*I-3),B(6*I-2),B(6*I-1),B(6*I),K
       STOP
       END
8784   0
```

Figure 23.   Fortran Program for Compressing Hourly Load Data
by Taking 12-Hour Averages

```
C  PROGRAM FOR REDUCING THE NUMBER OF DATA POINTS
C  AVERAGES FOR 12-HOUR INTERVALS
       DIMENSION A(9600),B(800)
     1 FORMAT (6F12.1)
     2 FORMAT (2I4)
     3 FORMAT (6F12.5X,I3)
       READ (5,2)M,N
       READ (5,1) (A(I),I=1,M)
       DO 300 I=1,M
       CB=A(I)*A(I)*A(I)
   300 A(I)=CB
       L=M/12
       DO 500 I=1,L
       SUM=A(12*I-11)+A(12*I-10)+A(12*I-9)+A(12*I-8)+A(12*I-7)+A(12*I-6)+
      2A(12*I-5)+A(12*I-4)+A(12*I-3)+A(12*I-2)+A(12*I-1)+A(12*I)
   500 B(I)=SUM/12.
       L=M/72
       K=N
       DO 900 I=1,L
       K=K+1
   900 WRITE (7,3) B(6*I-5),B(6*I-4),B(6*I-3),B(6*I-2),B(6*I-1),B(6*I),K
       STOP
       END
8784   0
```

Figure 24.   Fortran Program for Compressing Hourly Wind Data by
Taking 12-Hour Averages of the Wind Velocities Cubed

and the resulting 732 computed output points exactly fill 122 cards.
When utilized in the GPSS program, only 730 points are used so no harm
is done by the extra points and the Fortran program is simplified.

The averaging process for the wind velocity data is basically the
same but an additional step is required. Since the wind power is pro-
portional to its velocity cubed, the useful information is the average
of the cubes of the 12 successive velocity readings. Figure 24 shows
the program for reading in the 8784 points, cubing each point, aver-
aging these cubes 12 at a time, and punching out the resulting 732
points along with a card identification number on 122 cards.

APPENDIX C

PROGRAM FOR DETERMINING TOTAL STORAGE ENERGY OUTPUT

In order to determine the total storage energy output, one must
know the load demand versus time and the transfer function, power out
versus power in, from storage to load. GPSS is used in making this
calculation because of the ease of representing the transfer function
and the fact that interpolation between points is performed automat-
ically in GPSS by denoting the function as a continuous function. The
portion of the system, the output portion, under consideration is
shown in Figure 25 . Since the desired quantity is the output energy
from the storage unit, the load demand is referred back to the storage
through the output transfer function. This referral is accomplished
by "inverting" the transfer function. The inverted transfer function
might be more properly designated as the arc transfer function. This
inversion is accomplished as shown in Figure 26 by plotting the output
of the transfer function along the abscissa and the input to the trans-
fer function along the ordinate.

The program for making the desired calculation is shown in Figure
27. The numbers used to denote functions, variables, etc. occur in
a random manner since most of the cards were already punched for use in
other programs. The first two cards are not numbered; they are used to
reallocate space from unused entities to Common core. This realloca-
tion is necessary because of the large number of points processed. The
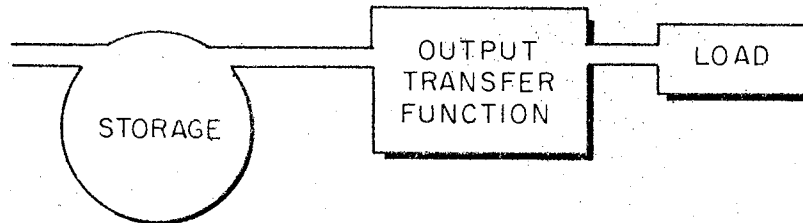
Figure 25. Block Diagram of the Output Portion
of the Power System
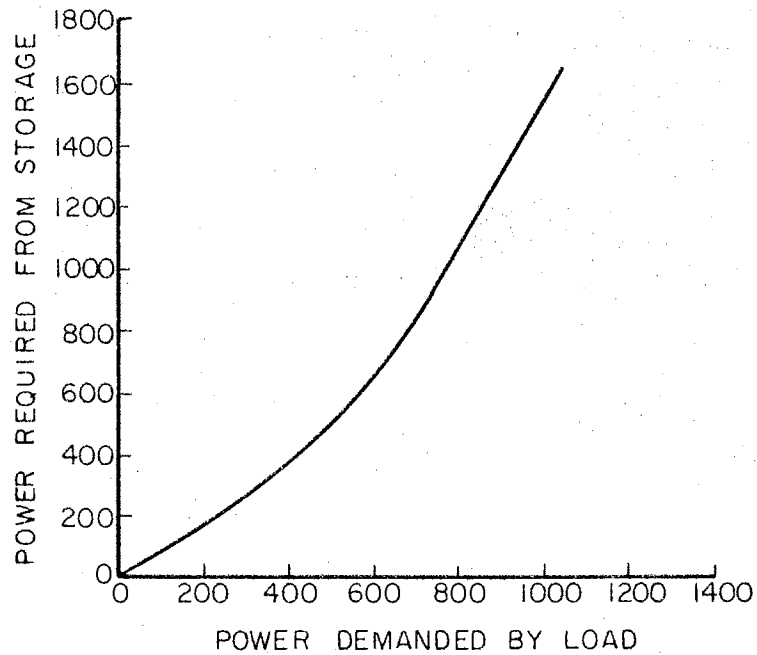
Figure 26. Example of Arc Output Transfer
Function

```
REALLOCATE XAC,50,FAC,0,STO,10,QUE,0,LOG,10,FUN,20,VAR,25,CHA,0
REALLOCATE GRP,0,BVR,0,FMS,0,HMS,0,COM,120000
```

*LOC	OPERATION	A,B,C,D,E,F,G	COMMENTS				CARD NUMBER
	SIMULATE						1
*	PROGRAM FOR DETERMINING LOAD DEMAND FROM STORAGE						2
2	FUNCTION	XH2,L8760	ENERGY DEMAND CURVE				3
	334.2	307.9	282.9	277.9	281.1	282.9	4
	-	-	-	-	-	-	-
	551.9	523.9	495.2	441.0	425.3	391.8	1463
9	FUNCTION	X381,C4	NORMALIZED INVERTED OUTPUT TRANSFER FCN				1464
0	0 335	445 638	889 1000 1634				1465
5	VARIABLE	X380*1000/XH13	NORMALIZED LOAD DEMAND				1466
6	VARIABLE	FN9*XH13/1000	RESCALE ENERGY REMOVED FROM STORAGE				1467
	INITIAL	XH13,1000	PEAK LOAD DEMAND				1468
	GENERATE	1	GENERATE OPERATING TRANSACTIONS				1469
	SAVEVALUE	2+,1,H	INCREMENT XH2				1470
	SAVEVALUE	380,FN2	LOAD DEMAND IN X380				1471
	SAVEVALUE	381,V5	NORMALIZE LOAD DEMAND				1472
	SAVEVALUE	382,V6	ENERGY TO BE REMOVED FROM STORAGE				1473
	TABULATE	5	TABULATE LOAD DEMAND FROM STORAGE				1474
	SAVEVALUE	399-,X382	REMOVE ENERGY				1475
	TERMINATE	1	REMOVE TRANSACTION, COUNT ONE				1476
5	TABLE	X382,0,100,52	STORAGE OUTPUTS IN TBL 5				1477
	START	8760					1478
	END						1479

Figure 27.   GPSS Program for Determining the Total
Energy Output Required From Storage

various functions, Variables, Savevalues, and other entities require

allocations from this Common core storage and the 8760 data points

alone need 35040 bytes from Common. Since Common normally has only

14400 bytes, a reallocation is necessary. The load demand is entered

as Function 2 and will be read as a function of time, one point per

hour for 8760 hours. In this program one clock unit equals one hour.

Only the first and last card of the 1460 data cards are shown; the

remaining 1458 are represented by the dashed lines. The normalized

inverted output transfer function is Function 9. Only a few points are

needed; the program performs linear interpolation between points.

Variable 5 normalizes the load demand with respect to one kilowatt and

Variable 6 performs the calculation of referring the normalized load

back through the normalized output transfer function and rescaling it.

Half-word Savevalue 13, XH13, contains the peak load demand which is

used to normalize the load with respect to one kilowatt.

The operational portion of the program begins with the Generate

card, card number 1469, which causes transactions to be generated at

the rate of one per clock unit. These transactions travel down through

the program and trigger the action on each card encountered. Card 1470

causes the clock units to be counted and the current value of the sum

to be maintained in XH2. This sum is the argument for Function 2.

Card 1471 causes the corresponding load demand point to be read from

Function 2 and stored in Savevalue 380, X380. Card 1472 causes Vari-

able 5 to normalize the load demand and then stores this result in

X381. Card 1473 causes the normalized load to be referred back through

the normalized output transfer function and be rescaled by Variable 6.

The result is stored in X382. Card 1474 causes the tabulation of the

contents of X382, the quantities removed from storage each hour. This statistical information is obtained as a bonus by the use of only two cards, this tabulation card and the table definition card described later. The next card, number 1475, removes the necessary energy from storage, X399. The final card within the active program is a terminate care, card number 1476, which removes the transaction from the program and adds a count of one to the tally of transactions. Card 1476 is a table definition card. It defines Table 5 as tabulating the contents of X382, starting the tabulation at zero, having 100 watt-hours per interval (except for the first and last which are always semi-infinite) and tabulating a total of 52 intervals. These 52 intervals have one interval for zero and below, 50 intervals of 100 watt-hours each, and one interval for all values above 5000 watt-hours. Card 1478 sets the transaction tally total at 8760 and starts the program to operating. Card number 1479 signals the compiler that these are all of the cards for this program. The results of using this program on the load data of the example case show a total energy demand from storage of 5883529 watt-hours.

APPENDIX D

GPSS PROGRAM FOR GRID SEARCH USING COMPRESSED DATA

The major portion of the investigation of various combinations of
the three variable parameters was performed by using the program of
Figure 28. The general objective of the program is to perform a rough
simulation by using the 12-hour averages for both wind power and load
demand. The input data points are the 12-hour averages of the cubes of
the wind velocities and the load demand data points are the 12-hour
averages of the hourly load demands.

The program performs a simulation using a given combination of
storage capacity, generator size, and wind intercept area. The mini-
mum storage content is checked and the wind intercept area is changed
by a correction factor. This correction factor is calculated to cause
the minimum storage content to come closer to the preset design value.
A second simulation is then performed and system costs for the variable
components are calculated. The storage capacity is not changed but
another generator size and trial wind intercept area are selected and
the process of simulation, adjustment of area, and simulation is re-
peated. This sequence continues for as many generator sizes as de-
sired. Detailed operation of the program follows for those persons who
are familiar with GPSS. Some operational suggestions for reducing the
time and effort are included at the end of this section.

The program of Figure 28 may start with two Reallocate cards whose

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```
                                                                     CARD
*LOC    OPERATION  A,B,C,D,E,F,G              COMMENTS               NUMBER
        SIMULATE                                                        1
*  ABBREVIATED PROGRAM USING CONDENSED DATA                             2
*  COST IN CENTS OF SYSTEM VARIABLE COMPONENTS IN X400                  3
*  GENERATOR SIZE IN WATTS IN XH5                                       4
*  WIND INTERCEPT AREA IN SQUARE FEET IN XH4                            5
*  STORAGE CAPACITY IN WATT-HOURS IN X398                               6
     1 FUNCTION   XH1,L732     WIND POWER DATA                          7
        -          -           -        -       -       -        -      -
     2 FUNCTION   XH2,L732     ENERGY DEMAND DATA                     130
        -          -           -        -       -       -        -      -
     3 FUNCTION   X399,C2      ENERGY LEAKAGE FUNCTION                253
0       0   99000099                                                  254
     5 FUNCTION   X373,C6      GENERATOR TRANSFER FUNCTION            255
79      0    80     20    200    80    1250  1000  16000 1000  16001 0 256
     7 FUNCTION   X370,C12     PROPELLER TRANSFER FUNCTION            257
105     0   216     33    343    80    512   159    729   255  1331 533 258
3375  1350 6859   2490  12167  3920  21952 5980  32768 7610  46656 8950 259
     8 FUNCTION   X374,C6      NORMALIZED STORAGE INPUT TRANSFER FUNCTION 260
0       0    40     36     83    72    219   180    465   360  1000 720 261
     9 FUNCTION   X380,C4      NORMALIZED STORAGE OUTPUT TRANSFER FCN  262
0       0   335    445    638  "889   1000  1634                       263
    10 FUNCTION   XH4,C6       PROPELLER COST CURVE IN CENTS PER SQ FT 264
0       0     1    500      5   1500   10    2000  100   15000 1000 150000 265
    11 FUNCTION   XH12,L12     GENERATOR SIZE                         266
     1400            1600           1800           2000        2200      2400  267
     2600            2800           3000           3200        3400      3600  268
    12 FUNCTION   XH12,L12     CORRESPONDING TRIAL WIND INTERCEPT AREA 269
     1250            850            720            650         625       600   270
     590            580            590            600         610       620   271
     1 VARIABLE    FN10+XH7*XH5/1000+XH8*X398/10000  INCREMENTAL COST  272
     2 VARIABLE    X371*XH4*81/10000  CONVERT WIND VEL CUBED INTO POWER 273
     3 VARIABLE    X372*1000/XH5  NORMALIZE W.R.T. ONE KILOWATT        274
     4 VARIABLE    FN8*XH5/1000  ENERGY TO STORAGE                     275
     5 VARIABLE    FN9*12*XH13/1000  RESCALE ENERGY REMOVED FROM STORAGE 276
     6 VARIABLE    X380*1000/XH13  NORMALIZE LOAD DEMAND W.R.T. ONE KW 277
     7 VARIABLE    X375*12    MULTIPLY BY 12 HOURS                     278
     8 VARIABLE    X399/1000    STORAGE CAPACITY IN KWH                279
     9 VARIABLE    X400/100    COST IN DOLLARS OF VARIABLE COMPONENTS  280
    10 VARIABLE    X374*XH5/1000  RESCALE ENERGY GENERATED            281
    11 VARIABLE    X396-X397    TOTAL STORAGE REQUIRED                 282
    12 VARIABLE    X395-X397+25000  PREPARE TO ADJUST AREA             283
    13 VARIABLE    XH4*V12/X395  ADJUST AREA                          284
       INITIAL     XH4,1250     START WITH FIRST AREA                  285
       INITIAL     XH5,1400     START WITH FIRST GENERATOR             286
       INITIAL     XH7,17000    COST OF GEN AND EL CELL IN CENTS/KW    287
       INITIAL     XH8,833      COST OF STORAGE IN MILS/KWH            288
       INITIAL     XH11,730     NUMBER OF DATA POINTS                  289
       INITIAL     XH12,1       START WITH FIRST GENERATOR             290
       INITIAL     XH13,1000    LOAD NORMALIZATION FACTOR - PEAK LOAD  291
       INITIAL     X398,100000  DEFINE STORAGE CAPACITY                292
       INITIAL     X399,100000  START WITH EXPECTED AMOUNT IN STORAGE  293
       GENERATE    1,,,1        GENERATE INITIALIZING TRANSACTION      294
       SAVEVALUE   397,X399     INITIALIZE MINIMUM STORAGE CONTENT     295
       SAVEVALUE   394,0        START WITH ZERO IN SUMMATION           296
       SAVEVALUE   395,0        START WITH ZERO IN SUMMATION           297
       TERMINATE                REMOVE TRANSACTION                     298
       GENERATE    1200,,,4     GENERATE OPERATING TRANSACTIONS        299
       SAVEVALUE   1+,1,H       INCREMENT XH1                          300
       SAVEVALUE   2+,1,H       INCREMENT XH2                          301
       SAVEVALUE   3+,1,H       INCREMENT XH3                          302
```

```
       SAVEVALUE   370,FN1      WIND VELOCITY CUBED IN X370            303
       SAVEVALUE   371,FN7      WIND VEL CUBED ALTERED BY PROP EFF     304
       SAVEVALUE   372,V2       SHAFT POWER IN X372                    305
       SAVEVALUE   373,V3       NORMALIZE TO ONE KILOWATT              306
       SAVEVALUE   374,FN5      ELECTRICAL POWER GENERATED PER RATED KW 307
       SAVEVALUE   375,V4       RESCALE ENERGY TO STORAGE              308
       SAVEVALUE   399+,V7      STORE ENERGY FOR PREVIOUS TWELVE HOURS 309
       SAVEVALUE   394+,V7      INTEGRATE ENERGY                       310
       SAVEVALUE   380,FN2      LOAD DEMAND IN X380                    311
       SAVEVALUE   381,V6       NORMALIZED ENERGY DEMAND               312
       SAVEVALUE   382,V5       ENERGY TO BE REMOVED FROM STORAGE      313
       SAVEVALUE   399-,X382    REMOVE ENERGY                          314
       SAVEVALUE   6,FN3,H      CALCULATE ENERGY LEAKAGE               315
       SAVEVALUE   399-,XH6     REMOVE LEAKAGE ENERGY                  316
       TEST G      X399,X398,CONT  IF STOR LIMIT EXCEEDED, DISCARD EXCESS 317
       SAVEVALUE   399,X398     DISCARD EXCESS                         318
       SAVEVALUE   394,0        CLEAR INTEGRAL                         319
       SAVEVALUE   395,0        CLEAR TOTAL INTEGRAL                   320
CONT   SAVEVALUE   3+,0,H       PROVIDE BRANCH POINT, CONT             321
       SAVEVALUE   XH3,X399     RECORD ENERGY CURRENTLY IN STORAGE     322
       TEST L      X399,X397,CNT  TEST MINIMUM STORAGE CONTENT         323
       SAVEVALUE   397,X399     RECORD NEW MINIMUM                     324
       SAVEVALUE   395+,X394    ADD INTEGRAL COMPONENT                 325
       SAVEVALUE   394,0        CLEAR INTEGRAL                         326
CNT    SAVEVALUE   3+,0,H       PROVIDE BRANCH POINT, CNT              327
       TEST L      XH1,XH11,END TEST FOR END OF RUN                    328
       TEST E      XH3,365,DNTP IF XH3=365, PRINT                      329
       PRINT       1,365,X      PRINT SAVEVALUES 1 THROUGH 365         330
       SAVEVALUE   3,0,H        CLEAR XH3                              331
DNTP   SAVEVALUE   3+,0,H       PROVIDE BRANCH POINT, DNTP             332
       TERMINATE                REMOVE TRANSACTION                     333
END    SAVEVALUE   3+,0,H       PROVIDE BRANCH POINT, END             334
       TEST L      XH15,5,CHGN  IF XH15 IS GREATER THAN 4, CHGN        335
       SAVEVALUE   14,V13,H     STORE MODIFIED AREA TEMPORARILY        336
       SAVEVALUE   4,XH14,H     REPLACE AREA                           337
       SAVEVALUE   15,10,H      PLACE 10 IN XH15                       338
       TERMINATE   1            REMOVE TRANSACTION, COUNT ONE          339
CHGN   SAVEVALUE   3+,0,H       PROVIDE BRANCH POINT, CHGN             340
       SAVEVALUE   400,V1       CALCULATE COST, STORE IN X400          341
       SAVEVALUE   15,0,H       PLACE ZERO IN XH15                     342
       SAVEVALUE   12+,1,H      INCREMENT XH12                         343
       SAVEVALUE   5,FN11,H     CHANGE GENERATOR SIZE                  344
       SAVEVALUE   4,FN12,H     USE CORRESPONDING TRIAL WIND AREA      345
       SAVEVALUE   399,X398     REINITIALIZE STORAGE CONTENT           346
       TERMINATE   1            REMOVE TRANSACTION, COUNT ONE          347
       START       1            SET TRANSACTION COUNT AND BEGIN SIMULATION 348
       CLEAR       XH4-XH99,X398                                       349
       START       1            SET TRANSACTION COUNT AND BEGIN SIMULATION 350
       CLEAR       XH4-XH99,X398                                       351
       START       1            SET TRANSACTION COUNT AND BEGIN SIMULATION 352
       CLEAR       XH4-XH99,X398                                       353
       START       1            SET TRANSACTION COUNT AND BEGIN SIMULATION 354
       CLEAR       XH4-XH99,X398                                       355
       START       1            SET TRANSACTION COUNT AND BEGIN SIMULATION 356
       CLEAR       XH4-XH99,X398                                       357
       START       1            SET TRANSACTION COUNT AND BEGIN SIMULATION 358
       CLEAR       XH4-XH99,X398                                       359
       START       1            SET TRANSACTION COUNT AND BEGIN SIMULATION 360
       CLEAR       XH4-XH99,X398                                       361
       START       1            SET TRANSACTION COUNT AND BEGIN SIMULATION 362
       END                                                            363
```

Figure 28. GPSS Program for Performing Grid Search Using Abbreviated Simulation

function is to reallocate core capacity from unused entities to the

Common core area where it is needed. The column titles are automat-

ically provided by the GPSS compiler; the card numbers appearing in

the right-hand column are also inserted by the compiler. Card number

one is a Simulate card to cause the program to be executed; without

this card the program would only be compiled and checked for compile

errors. The next few cards are Comment cards; they may be identified

by a leading asterisk.

Input data, transfer functions, propeller cost function, and

tables of generator size and trial wind intercept area are read in as

functions beginning with card number seven. Cards listed as a series

of dashes represent large volumes of data cards. The number of data

cards omitted may be noted by checking the card numbers in the right

hand column. Card number seven defines Function 1 as a list function

with 732 data points and having Half-word Savevalue 1, XH1, as its

argument. The comment, which is optional, gives the information that

this function is wind power data. The cards following this one contain

the 732 data points with six per card.

Card number 130 defines Function 2 as a List function with 732

data points and having Half-word Savevalue 2, XH2, as its argument.

The optional comment reveals that this function is the energy demand.

Again the 732 data points are on the cards immediately following.

Card number 253 defines the energy leakage function, Function 3,

as a Continuous function with two points and having the contents of

Savevalue 399, X399, as its argument. Card number 254 gives the x_i, y_i

values in pairs for the two points 0,0 and 990000,99.

Card number 255 defines the generator transfer function, Function

5, as a Continuous function with six points and having Savevalue 373 as its argument. Card number 256 gives the six points for this transfer function.

Cards 257 through 271 define other functions similarly. A comment is in order regarding the two different types of functions used, Continusou functions and List functions. The Continuous functions are actually used as functions in the normal sense within the program. That is to say that various abscissa are specified and the corresponding ordinates are determined by interpolation. However, the List functions are used in a manner which could more aptly be described as processing sequential data. The List functions are not really functions but are merely used to insert data into the program.

Cards 272 through 284 define the Variables used. For example card number 278 may be read as Variable 7 equals 12 times the contents of Savevalue 375. These Variables are used within the program to perform arithmetic calculations.

Cards 285 through 294 initialize the contents of various Savevalue locations, both Half-word and full-word. In some cases these values will be changed as the program progresses; in other cases this initialization is a method for inserting constants into the program. To be explicit, in this program all of the initial cards except four are used to define constants; these constants are explained by the corresponding comments on the cards. Of the four cards used to initialize the contents of a Savevalue in the true sense, one is card 285 which sets the contents of XH4 to the first trial wind intercept area. Card 285 initializes the contents of XH5 to the size of the first generator used. Card 290 sets XH12 at one. XH12 keeps track of which

generator is currently being used. Card 293 sets the content of storage, X399, at approximately what it is expected to contain at the beginning of the simulation period under actual operating conditions. For practical purposes, since the simulation begins on January 1 and ends on December 31, the initial and final content of storage should be approximately the same. A few trial runs will determine approximately how much initial energy to place in the storage Savevalue.

Cards 294 through 298 are an initialization routine performed at the start of each simulation. This routine is necessary in addition to the initialization cards since an Initial card is effective only on the first simulation after it has been read into the program. Card 294 generates a transaction at clock time one and then becomes inactive. This transaction becomes a trigger to actuate the cards which follow. Card 295 records the current content of storage as the minimum. If this action is not taken, the zero initially in X397 or some previous minimum might be less than the true minimum for the current simulation and thereby produce erroneous results. Savevalues 394 and 395 are used as integrators; their use will be explained during the correction phase of the program. Cards 296 and 297 set these to zero at the beginning of each simulation. Card 298 removes this initializing transaction.

The simulation proper begins with card 299 which generates an operating transaction, or trigger, every 1200 clock units with an offset of 4 clock units. Thus, triggers occur at clock times of 4, 1204, 2404, 3604,..., until the simulation is terminated. Each 1200 clock units represents 12 hours. Cards 300, 301, and 302 provide a means for keeping track of the number of 12-hour periods by counting them in

XH1, XH2, and XH3 respectively. Three counters are needed since XH1 is
the argument for the wind data and is not reset during the simulation,
XH2 is the argument for the load which, for some cases, may be reset
every 168 hours to represent a weekly load cycle, and XH3 controls the
periodic printout so it must be reset every time it reaches 365, the
number of Savevalue locations reserved for the output data.

Card 303 transfers the desired data point from Function 1 into
X370. Card 304 acts upon the contents of X370 by specifying that the
output of Function 7 be placed in X371. Since X370 is the argument of
Function 7, the data point in X370 is acted upon by the propeller
transfer function and the result is stored in X371. At this point the
number is proportional to shaft power and must be multiplied by the
appropriate constants to convert to shaft power. Variable 2 multiplies
the contents of X371 by the necessary constants, the wind intercept
area and the constant or proportionality to convert wind velocity cubed
into watts per square foot. Card 305 causes this multiplication to
take place and the results to be stored in X372. The contents of X372
are, therefore, shaft power in watts. Variable 3 normalizes shaft
power with respect to one kilowatt so card 306 causes this normaliza-
tion to take place and the results, shaft power in watts per kilowatt
of generator rated power, are stored in X373. This normalization is
performed under the assumption that the generator transfer function may
be normalized; i.e. all transfer functions for a given type of machine
have the same shape but vary in size according to the generator rating.
Card 307 causes the normalized shaft power in X373 to be applied to the
normalized generator transfer function, Function 5, and the resulting
normalized generator output in watts per kilowatt of generator rating

is stored in X374. Function 8 is the transfer function of an electrolysis cell rated at one kilowatt. Under the assumption that the size of the electrolysis cell and its associated equipment will be scaled up or down according to the generator output rating, Variable 4 will define the operations of applying the normalized generator output to the normalized electrolysis cell transfer function and rescaling the resulting output. Card 308 causes Variable 4 to perform this operation and then stores the results in X375. Variable 7 causes the contents of X375 to be multiplied by 12. Card 309 calls for Variable 7 to be added to X399 thereby adding the energy generated during the previous 12 hours. Card 310 adds the same amount to X394 to obtain an integral of energy generated. This integral or sum of energy generated will be used in correcting the wind intercept area.

Card 311 shifts the appropriate load demand data point into X380. Since the fuel cell transfer function has been normalized to one kilowatt, the energy demand must also be normalized to one kilowatt. Card 312 uses Variable 6 to accomplish this normalization. The results are stored in X381. Card 313 uses Variable 5 to rescale the energy demand and multiply it by 12 hours. The results, the energy to be removed from storage, are stored in X382. Card 314 causes this energy to be removed from storage.

The energy leakage is calculated by card 315 using Function 3 and is removed from storage by card 316.

The maximum energy allowed in the storage unit has been read into X398 by Initial card number 292. Test card number 317 checks to see whether this limit has been exceeded. If so, card number 318 removes the excess energy from storage. Physically this would not have been

allowed to build up but would have been allowed to escape through a pressure valve. Cards number 319 and 320 clear the integrals of energy generated thus far. Card 321 is a "no operation" card used to provide the branch point to which card 317 branches if the storage content is less than or equal to the maximum allowable value. Card 322 records the current content of storage, X399, in the Savevalue whose number is given in XH3. Since XH3 is incremented by one each 12-hour interval, the storage content is recorded each noon and midnight.

Card 323 compares the current content of storage with the minimum value recorded so far and card 324 records the new minimum if there is one. Card 325 adds the contents of X394 to X395 and card 326 sets the contents of X394 to zero. Card 327 is the branch point for card 323 in case the current contents of storage are greater than the recorded minimum.

XH11 contains the number of data points in Function 1. As long as XH1 is less than XH11 the simulation should continue. Card 328 compares XH1 with XH11 and continues the simulation if XH1 is less than XH11.

The first 365 savevalue locations have been reserved for data which is to be printed out; in this case the data are the points of the time record of the contents of storage. Whenever XH3 contains the number 365 card number 322 stores a number in X365 which finishes filling the allotted savevalue spaces and card number 329 then routes the transaction to card 330 which causes the contents of X1 through X365 to be printed out. Card 331 then sets XH3 back to zero. Card 332 provides the branch point for card 329 whenever the contents of XH3 are not equal to 365. Card 333 removes the transaction from the

system.

In case the contents of XH1 are not less than XH11, card 328 will route the transaction to card 334. Whenever the transaction reaches card 334, its arrival signifies the end of a simulation run and initiates either a correction in the wind intercept area or the selection of a new generator size and corresponding trial wind intercept area. Card 335 tests the contents of XH15 to determine which to do. If the contents of XH15 are less than 5 then the wind intercept area is modified by card 336. This modification is a linear process; it is aimed at providing a minimum storage content of 25000 watt-hours. See Figure 29. Assume that the minimum occurs at point b; also assume that point a is the last time that the storage was full prior to point b. The total energy generated between a and b is to appear in X395 to be used in making the correction. Any energy accumulated in X394 or X395 prior to point a is discarded by cards 319 and 320 each time the storage limit is exceeded. After point a the accumulation of energy is recorded in X394 until point c is reached. At point c, card 323 routes a transaction through card 325 which adds to X395 the accumulated total energy generated between points a and c. Card 326 then clears the contents of X394. Each time a new minimum is recorded, the contents of X394 are added to X395. The contents of X394 are the accumulation of the energy generated since the previous transferral. This two-stage method is necessary because of a number of local minima which occur. Finally, at point b the last partial sum is added to X395. Even though X394 continues to accumulate another partial sum, it will not be used. The correction is accomplished by Variables 12 and 13. Variable 12 calculated the total energy which should have been
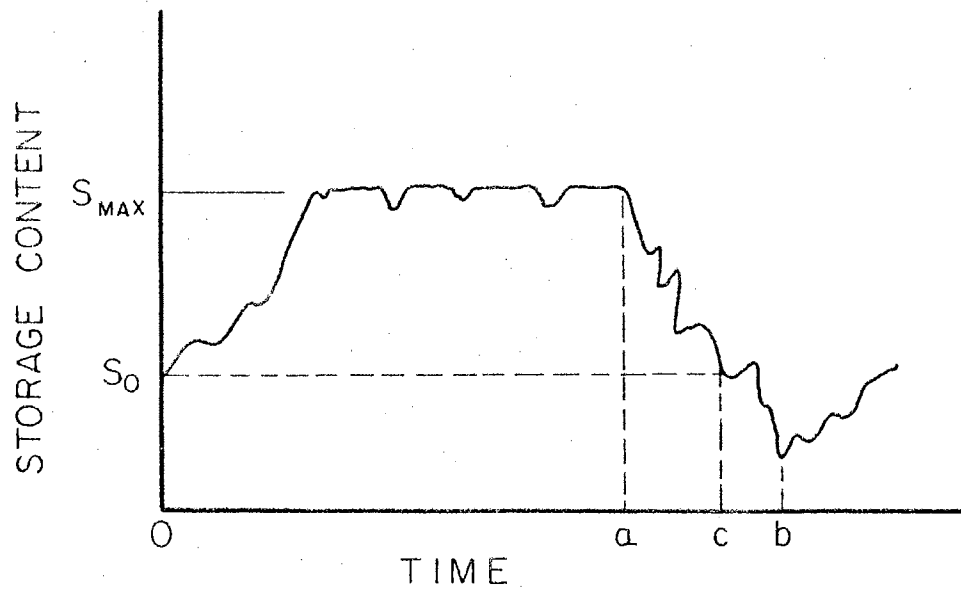
Figure 29. Typical Plot of Energy Storage Content
Versus Time for One Year Showing the
Effect of a Limited Storage Capacity

generated between points a and b in order to have the storage content

dip to the desired 25000 watt-hours at its minimum point. Variable 13

multiplies the wind intercept area in XH4 by the ratio of the desired

total generation to the actual total generation between points a and b.

Card 337 replaces the previous wind intercept area by the corrected

wind intercept area. Card 338 places a ten in XH15; any number greater

than four would have sufficed to reverse the results of the test of

card 335 after the next simulation is completed. The number five works

well on card 335 as a test criterion. If more than one correction had

been desired, card number 338 could have been written to add three to

XH15. This change would have caused the area to have been adjusted

twice before changing generators instead of only once. Four correc-

tions in area could have been accomplished by adding one to XH15 with

card 338.

As now written the program causes one simulation to be performed,

a correction to be applied to the wind intercept area, and a second

simulation to be performed. At the end of the second simulation, the

transaction is routed from card 335 to card 340 which is a branch point.

Card 341 caclulates the cost of the last system simulated and places

this cost in X400. Card 342 places a zero in XH15 to indicate that a

new generator is to be used in the next simulation. Card 343 incre-

ments XH12 in preparation for reading in new values for generator size

and wind intercept area. Card 344 and 345 read these new values into

XH5 and XH4, respectively, from Function 11 and Function 12 using the

contents of XH12 as arguments. Card 346 reinitializes the storage

content, X399. After having completed the second simulation and

changing generators, card 347 removes the transaction from the program

and provides the count necessary to satisfy card 350, the second Start card, with a count of one.

Refer back, momentarily, to the end of the first simulation after the wind intercept area has been corrected and a count from card 399 satisfies the count specified on card 348. Card 349 is the next card whose commands are executed. This Clear card uses the optional selective clear feature. The Clear card removes all accumulated statistics and sets all numbers to zero, including the clocks, except those designated in the field beginning in column 19 of the card. Notice that the counters XH1, XH2, and XH3 are set to zero but the values in the other Half-word Savevalues XH4 through XH99 are retained. Savevalue 398 contains the limiting size of the energy storage device so it must also be retained. Card 350 initiates the second simulation and is not satisfied until a transaction is counted by card 347 indicating the completion of the second simulation. One additional set of cards consisting of a Clear and a Start card is added for each additional simulation desired. For the program shown, there are eight start cards so four generator sizes would each have two simulations, one with the initial trial wind intercept area and a second one with the corrected wind intercept area. The final card, the End card, indicates to the computer that the program is completed.

In conclusion a practical hint for saving computer time will be offered. Considerable computer time can be saved by using only the pertinent portions of wind and load data. A single simulation using all the data takes less than one minute and will give a rough idea of the locations of points a and b of Figure 29 . By using only the data in this region plus a reasonable margin on each side, the computation

time may be reduced to approximately one fourth the time for the same

calculations using all the data. A second point to consider is the

fact that the correction scheme will not work as now written if the

storage unit is filled to capacity after point b of Figure 29 has

been reached. This is true because of the method used to keep the in-

tegrals clear prior to point a. All energy generated prior to point a

was discarded from the correction integrals each time there was excess

energy to discard; the same procedure sets the correction terms to

zero after point b has been reached if the energy storage unit again

becomes completely full. This complete filling does occur for the

smaller values of storage capacities. Therefore, it is necessary to

discard all data to the right of point b that would indanger the cor-

rection integrals and it is advantageous, timewise, to discard most of

the data to the left of point a. Since this starting place occurs at

a time when the storage unit is filled to capacity, cards 293 and 346

should always initialize the storage to its full state. After each

point of the search grid has been calculated by use of the abbreviated

data, a simulation using the complete data will insure that the results

are valid.

APPENDIX E

FULL-SCALE SIMULATION PROGRAM

After the region of interest, the grid of parameter values, has been investigated by using the compressed-data program, the most promising points on the grid should be investigated by a full simulation. The program for this simulation is given in Figure 30 . Many portions of this program are similar to corresponding sections of the program given in Appendix D so the reader is referred to that program for a detailed explanation of the segments not explained fully here.

This program begins with Reallocate, Simulate and Comment cards as did the previous program. Data are fed into the program as functions. Transfer functions and Variables are defined as explained in Appendix D. However, one noteworthy point involves Variable 2. Since the arithmetic proceeds from left to right with multiplication and division occupying equal positions in the hierarchy of operations, this Variable was written in such a manner that a sufficient number of significant figures would be retained for the smaller velocities yet the larger velocities would not overflow the capacity of the facility. The Initial cards serve the same capacities as before; there is no need for a reinitializing routine at the start of this program since it is not intended for repetitive use.

The simulation begins with card 2956 which generates a transaction every 100 clock units beginning at clock time four. Thus, every hour

```
REALLOCATE XAC,50,FAC,0,STO,10,QUE,0,LOG,10,FUN,20,VAR,25,CHA,0
REALLOCATE GRP,0,BVR,0,FMS,0,HMS,0,COM,120000
```

				CARD
*LOC	OPERATION	A,B,C,D,E,F,G	COMMENTS	NUMBER
	SIMULATE			1
*	FULL SCALE SIMULATION			2
1	FUNCTION	XH1,L8760	WIND VELOCITY DATA	3
-		-	-	-
2	FUNCTION	XH1,L8760	LOAD DEMAND DATA	1464
-		-	-	-
3	FUNCTION	X399,C2	ENERGY LEAKAGE FUNCTION	2925

```
C    C    .999000198                                                         2926
      4 FUNCTION  RN1,C15     ARC ERROR FUNCTION, SIGMA = 0.2               2927
0      0    .001   40   .006  50   .023  60   .067  70   .159  80          2928
.308  90   .500   100  .692  110  .841  120  .933  130  .977  140          2929
.994  150  .999   160  1.0000200                                           2930
      5 FUNCTION  X373,C6     NORMALIZED GENERATOR TRANSFER FUNCTION        3931
      5 FUNCTION  X373,C6     NORMALIZED GENERATOR TRANSFER FUNCTION        2931
79     0    80    20   200   80   1250  1000  16000 1000  16001 0          2932
      6 FUNCTION  XH6,C6      GUST EXTRACTION EFFICIENCY CURVE              2933
0     100   100   100  120   119  130   127   160   140   200   150        2934
      7 FUNCTION  X370,C13    PROPELLER TRANSFER FUNCTION                   2935
105    0    216   33   343   80   512   159   729   255   1331  533        2936
3375  1350  6859  2490 12167 3920 21952 5980  32768 7610  46656 8950       2937
37324871600                                                                2938
      8 FUNCTION  X374,C6     NORMALIZED STORAGE INPUT TRANSFER FUNCTION    2939
0      0    40    36   83    72   219   180   465   360   1000  720        2940
      9 FUNCTION  X381,C4     NORMALIZED STORAGE OUTPUT TRANSFER FCN        2941
0      0    335   445  638   889  1000  1634                               2942
      1 VARIABLE  X368*FN6    EFFECTIVE INSTANTANEOUS WIND VELOCITY         2943
      2 VARIABLE  X369*X369/1000*X369/1000  CUBE INST EFF VEL AND RESCL     2944
      3 VARIABLE  X371*XH4*81/10000  CALC SHAFT POWER                       2945
      4 VARIABLE  X372*1000/XH5  NORMALIZE SHAFT PWR W.R.T. ONE KW          2946
      5 VARIABLE  FN8*XH5/1000  CALC AND RESCALE GEN PWR OUTPUT             2947
      6 VARIABLE  X375/10     CALC ENERGY TO STORAGE                        2948
      7 VARIABLE  X380*1000/XH13  NORMALIZE ENERGY DEMAND W.R.T. ONE KW     2949
      8 VARIABLE  FN9*XH13/10000  CALC AND RESCALE ENGY FROM STORAGE        2950
        INITIAL   XH4,1080    WIND INTERCEPT AREA                           2951
        INITIAL   XH5,1800    GENERATOR SIZE                                2952
        INITIAL   XH13,1000   PEAK LOAD DEMAND                              2953
        INITIAL   X398,100000 STORAGE CAPACITY                              2954
        INITIAL   X399,100000 START WITH INITIAL ESTIMATE IN STORAGE        2955
        GENERATE  100,,4      GENERATE HOURLY TRANSACTIONS                  2956
        SAVEVALUE 1+,1,H      INCREMENT XH1                                 2957
        SAVEVALUE 368,FN1     READ HOURLY WIND VELOCITY                     2958
        SAVEVALUE 380,FN2     READ HOURLY LOAD DEMAND                       2959
        TERMINATE 1           REMOVE TRANSACTION, COUNT ONE                 2960
        GENERATE  10          GENERATE OPERATING TRANSACTIONS               2961
        SAVEVALUE 6,FN4,H     WIND GUST FACTOR IN XH6                       2962
        SAVEVALUE 369,V1      EFF INST WIND VEL TIMES 100 IN X369           2963
        SAVEVALUE 370,V2      WIND VEL CUBED IN X370                        2964
        SAVEVALUE 371,FN7     WIND VEL CUBED ALTERED BY PROP EFF            2965
        SAVEVALUE 372,V3      SHAFT POWER IN X372                           2966
        TABULATE  1           TABULATE SHAFT POWER                          2967
        SAVEVALUE 373,V4      NORMALIZE W.R.T. ONE KILOWATT                 2968
        SAVEVALUE 374,FN5     ELECTRICAL PWR GENERATED PER RATED KW         2969
        SAVEVALUE 375,V5      CALC AND RESCALE ENERGY TO STORAGE            2970
        TABULATE  2           TABULATE ELECTROLYSIS CELL OUTPUT             2971
        SAVEVALUE 399+,V6     STORE ENERGY FROM PREVIOUS 0.1 HOUR           2972
        SAVEVALUE 381,V7      NORMALIZE ENERGY DEMAND                       2973
        SAVEVALUE 382,V8      CALC AND RESCALE ENERGY FROM STORAGE          2974
        SAVEVALUE 399-,X382   REMOVE ENERGY                                 2975
        TABULATE  3           TABULATE DAILY STORAGE CONTENT                2976
        TERMINATE             REMOVE TRANSACTION                            2977
        GENERATE  2400,,608   GENERATE RECORDING TRANSACTIONS               2978
        SAVEVALUE 399-,FN3    ENERGY LEAKAGE                                2979
        SAVEVALUE 3+,1,H      INCREMENT XH3                                 2980
        TEST G    X399,X398,CONT  IF STG LIMIT EXCEEDED, DISCARD EXCESS     2981
        SAVEVALUE 399,X398    DISCARD EXCESS                                2982
CONT    SAVEVALUE 3+,0,H      PROVIDE BRANCH POINT,CONT                     2983
        SAVEVALUE XH3,X399    RECORD ENERGY CURRENTLY IN STORAGE            2984
        TERMINATE             REMOVE TRANSACTION                            2985
      1 TABLE     X372,0,100,52  SHAFT POWER IN TABLE 1                     2986
      2 TABLE     X375,0,100,32  ELECTROLYSIS CELL OUTPUT IN TABLE 2        2987
      3 TABLE     X399,0,10000,52  DAILY STORAGE CONTENT IN TABLE 3         2988
        START     8760        SET TRANSACTION COUNT AND START SIMULATION    2989
        END                                                                2990
```

Figure 30. GPSS Program for Performing a Full-Scale Simulation of the Power System for One Year

of simulation time, a transaction is generaged here. Card number 2957

increments XH1 which is to be the argument for both wind and load data.

Cards 2958 and 2959 transfer wind velocity and load demand data into

X368 and X380, respectively. Card 2960 then removes the transaction

from the system and decrements by one the count set by card 2989, the

Start card. Card 2961 generates a transaction every ten clock units

with no offset; these transactions trigger the wind gust simulations.

Card 2962 stores a wind gust factor in XH6 from Function 4 which uses

Random Number Generator 1 as its argument. These wind gust factors are

numbers between 0 and 200 distributed normally about 100 with a stan-

dard deviation, sigma, of 0.2. The choice of an appropriate sigma is

discussed by Merchant (39). The wind gust factor in XH6 is the argu-

ment for Function 6, the gust extraction efficiency curve. This func-

tion relates the extractable energy in a wind gust to its increase or

decrease from the average value. During a lull, the propeller will

slow down and extract the same energy from the wind as if it had been

constant at that value before the lull. But during a gust, the fixed-

pitch propeller does not intercept the wind at the proper angle to be

accelerated in the same proportion that it was decelerated for the

lull. Therefore, a gust extraction efficiency curve is used to relate

the percent of energy extracted from a gust to the size of the gust

(as a percentage of the average value). This percentage is then mul-

tiplied by the average velocity in X368 to obtain the scaled effective

wind velocity to store in X369. Card 2963 uses Variable 1 in accom-

plishing these actions. Card 2964 causes this scaled effective wind

velocity to be cubed and divided by one million to remove the scale

factor. Card 2965 applies this effective instantaneous velocity cubed

to the propeller transfer function, Function 7, to obtain a number proportional to shaft power and store this number in X371. Card number 2966 uses Variable 3 to cause the contents of X371 to be multiplied by the wind intercept area and the appropriate constant to obtain shaft power in watts. This power is stored in X372 where card 2967 can use it to tabulate shaft power in Table 1. Card 2968 uses Variable 4 to normalize this power to watts per kilowatt of rated generator power. This normalized shaft power is stored in X373 where it becomes the argument for Function 5. Card 2969 takes the electrical power generated in watts per rated generator killowat from Function 5 and stores this number in X374. Card 2970 uses Variable 5 to apply this normalized generated power to the normalized electrolysis cell transfer function, Function 8, and rescale it before storing it in X375. Card 2971 tabulates the electrolysis cell output in Table 2. Since the simulation period covered by the passage of one transaction is 0.1 hour, the quantity in X375 must be multiplied by 0.1 to obtain energy stored in watt-hours. Card 2972 uses Variable 6 to accomplish this multiplication by 0.1 and then adds the resulting energy to storage, X399.

Card 2973 uses Variable 7 to normalize the load demand with respect to one kilowatt. Card 2974 uses Variable 8 to apply the normalized load demand in X381 to Function 9 to obtain the normalized demand from storage. Variable 8 also removes the normalizing scale factor and multiplies by the necessary 0.1 factor. The resulting energy demand is stored in X382. Card 2975 causes this demand to be removed from storage, X399. Note that there is no Tabulate card for the demand from storage; it is not necessary since that information has already been obtained from the program of Appendix C. However, at this point

card 2976 tabulates the storage content in Table 3. Card 2977 then removes the transaction from the system.

Card 2978 generates a transaction every 24 hours, 2400 clock units, offset by slightly less than 6.1 hours. This offset causes the actions triggered by these transactions to appear to occur at 6:00 a.m. of each day. Card 2979 removes the energy leakage from storage. Note that the leakage function has been doubled from the previous program since the leakage energy is removed only once every 24 hours in this program as compared to 12 hours in the previous program. Card 2980 increments XH3 to provide the proper address for the recording of the current contents of energy storage. Cards 2981, 2982, and 2983 test for excess energy in storage, remove it if there is an excess, and provide a branch point for skipping card 2982 if there is no excess. Note that the removal of excess energy occurs only at 6:00 a.m. of each day in the simulation whereas in actual practice the excess energy would be removed continually by an over-pressure valve. This lack of correspondence will cause a few tabulations to appear in Table 3 at values greater than the storage limit. By moving these tabulations down to the storage limit, the correct results will be obtained. Card 2984 causes the current content of the energy storage unit to be recorded in the Savevalue whose number is the contents of XH3. Card 2985 removes the transaction from the program. Note that there is no need for an auxiliary printout in this program since the energy storage content is recorded only once per day and there are 365 savevalue locations reserved for these data.

Cards 2986, 2987, and 2988 define Tables 1, 2, and 3, respectively. Each definition card gives the entity tabulated, the lower limit

of interest, the interval size, and the number of intervals.

Card 2989 sets the number of transactions to be passed through card number 2960 and starts the simulation. Card 2990 signals the compiler that there are no more cards to be processed.

APPENDIX F

ADDING SOLAR ENERGY TO THE PREVIOUS SIMULATION PROGRAM

The current emphasis on space exploration has stimulated research on solar cells. These cells, which convert sunlight directly into electrical energy, are quite expensive at the present time. However, if the anticipated reduction in cost does materialize, investigations should be made into the possibility of combining wind power and solar power in the same system. This combination is desirable since the yearly cycles of available energy from these two sources complement each other.

A program for simulating this combination system may be obtained by adding the cards of Figure 31 to the program of Figure 28 . Function 13 is the sunlight intensity data (12-hour averages for this particular program) and Function 14 is the normalized transfer function of a solar cell. These functions are inserted between cards 271 and 272 of Figure 28 .

Variable 1 would need an additional term to add the cost of the solar cell components; the present Variable 1 card would be replaced by the one shown. Variable 14 defines the total energy output from the solar cell by multiplying the normalized output by the solar cell area and the proper constant of proportionality for the units chosen.

The two initial cards would be inserted between cards 291 and 292 in the program of Figure 28. As shown this additional set of cards

```
13 FUNCTION     XH1,L732     SUNLIGHT INTENSITY DATA

14 FUNCTION     FN13,C6      NORMALIZED SOLAR CELL TRANSFER FUNCTION


 1 VARIABLE     FN10+XH7*XH5/1000+XH8*X398/10000+XH15*XH16   INCR COST
14 VARIABLE     X393*XH15*KSC  MULT BY AREA AND SOLAR CELL CONSTANT

   INITIAL      XH15,SIZE    SOLAR CELL AREA IN SQUARE FEET
   INITIAL      XH16,COST    SOLAR CELL COST IN CENTS PER SQUARE FOOT

   SAVEVALUE    393,FN14     NORMALIZED SOLAR CELL OUTPUT
   SAVEVALUE    392,V14      CALCULATE SOLAR POWER
   SAVEVALUE    375+,X392    ADD SOLAR CELL COMPONENT OF POWER
```

Figure 31. Additional Cards Needed for the Abbreviated
            Program of Figure 28 to Simulate a
            Composite Wind and Solar Powered
            System

does not provide for a means of varying the solar cell area; it is set by XH15. If desired, this area could be varied by using some scheme similar to the one used to replace the wind intercept area in XH4 from Function 12.

The three cards indicating savevalue manipulations cause the solar contribution to be calculated and added to the wind energy already in X375. These cards should be inserted between cards 308 and 309.

APPENDIX G

PROPOSED DESIGN FOR A SELF-ADJUSTING,

VARIABLE-PITCH PROPELLER

One desirable characteristic of a device for extracting energy from winds is its ability to extract the maximum amount of energy from any velocity of wind regardless of how that velocity fluctuated with time. Certainly no propeller can extract all the energy from the wind but the variable-pitch propeller shown in Figure 32 should be able to extract more energy from varying winds than a constant pitch propeller. Its simplicity recommends it in preference to a controlled pitch propeller requiring sensors and actuators.

In developing this propeller one should determine what torque versus angular displacement characteristic, i.e. the spring characteristic, is needed for proper pitch control. Also, the division of the blade area in front of and behind its longitudinal axis needs to be considered since this division determines the torque transmitted to the spring for a given gust situation. These two areas are area A and area B, respectively, in Figure 32.

By reversing the direction of the spring, the self-adjusting feature could also be applied to light aircraft.
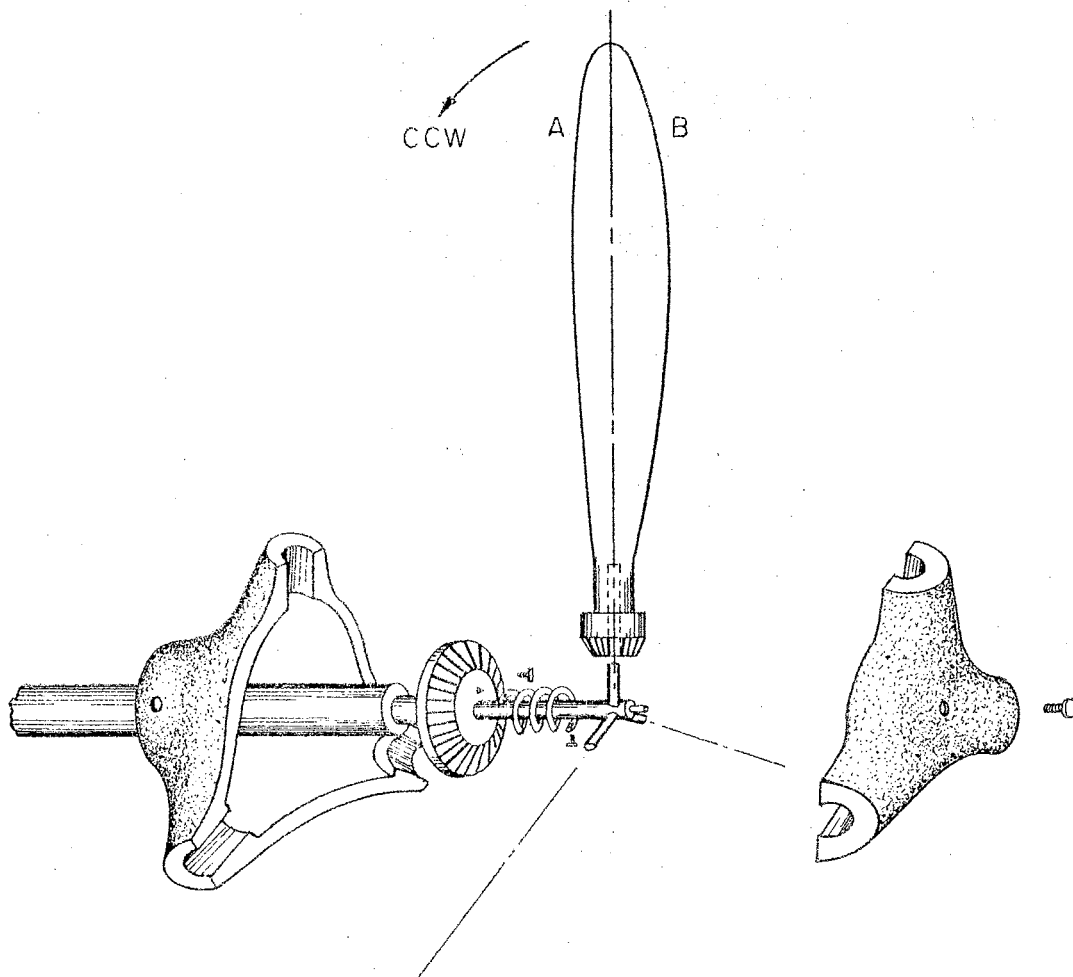
Figure 32.   Proposed Design for a Self-Adjusting,
Variable-Pitch Propeller

APPENDIX H

CONTROL CARDS FOR SIMULATION OF MULTIPLE POINTS

The search grid of Figure 16 can be covered in one pass through
the computer by the use of proper control cards at the end of the GPSS
program. Appendix D explains how converging simulations can be per-
formed at a point and then move to new values of generator size and
trial wind intercept area to repeat the process. This process will
simulate a horizontal row of the search grid if a sufficient number of
Start and Clear cards are placed at the end of the program just before
the End card.

In order to expand the coverage to include the entire grid, the
storage capacity must be redefined at the end of each row of simulation,
the generator size must be reinitialized, the generator counter must
be reset, the trial area must be reinitialized and the list of trial
areas, Function 12, must be redefined. These changes are accomplished
by the cards shown in Figure 33. Card number 371 redefines the storage
capacity. Card number 372 reinitializes the generator size. Card 373
resets the generator counter. Card 374 reinitializes the trial area
and Function 12 is redefined by cards 375 and 376. A group of cards
such as this with appropriate values must be used each time the simula-
tion shifts to the next higher value of storage capacity. Figure 33
shows the control cards needed to cover the search grid of Figure 16
with two simulations per point. Each set of dashes represents ten sets

```
START        1              SET TRANSACTION COUNT AND BEGIN SIMULATION    348
-            -              -          -          -          -            -
CLEAR        XH4-XH99,X398                                                369
START        1              SET TRANSACTION COUNT AND BEGIN SIMULATION    370
INITIAL      X398,200000    DEFINE STORAGE CAPACITY                       371
INITIAL      XH5,1400       START WITH FIRST GENERATOR                    372
INITIAL      XH12,1         START WITH FIRST GENERATOR                    373
INITIAL      XH4,700        START WITH FIRST AREA                         374
12 FUNCTION  XH12,L6        CORRESPONDING TRIAL WIND INTERCEPT AREA       375
700          550            500         475        450        450         376
CLEAR        XH4-XH99,X398                                                377
START        1              SET TRANSACTION COUNT AND BEGIN SIMULATION    378
-            -              -          -          -          -            -
CLEAR        XH4-XH99,X398                                                399
START        1              SET TRANSACTION COUNT AND BEGIN SIMULATION    400
INITIAL      X398,300000    DEFINE STORAGE CAPACITY                       401
INITIAL      XH5,1400       START WITH FIRST GENERATOR                    402
INITIAL      XH12,1         START WITH FIRST GENERATOR                    403
INITIAL      XH4,600        START WITH FIRST AREA                         404
12 FUNCTION  XH12,L6        CORRESPONDING TRIAL WIND INTERCEPT AREA       405
600          500            450         425        400        400         406
CLEAR        XH4-XH99,X398                                                407
START        1              SET TRANSACTION COUNT AND BEGIN SIMULATION    408
-            -              -          -          -          -            -
CLEAR        XH4-XH99,X398                                                429
START        1              SET TRANSACTION COUNT AND BEGIN SIMULATION    430
INITIAL      X398,400000    DEFINE STORAGE CAPACITY                       431
INITIAL      XH5,1400       START WITH FIRST GENERATOR                    432
INITIAL      XH12,1         START WITH FIRST GENERATOR                    433
INITIAL      XH4,550        START WITH FIRST AREA                         434
12 FUNCTION  XH12,L6        CORRESPONDING TRIAL WIND INTERCEPT AREA       435
550          450            400         375 .      360        360         436
CLEAR        XH4-XH99,X398                                                437
START        1              SET TRANSACTION COUNT AND BEGIN SIMULATION    438
-            -              -          -          -          -            -
CLEAR        XH4-XH99,X398                                                459
START        1              SET TRANSACTION COUNT AND BEGIN SIMULATION    460
INITIAL      X398,500000    DEFINE STORAGE CAPACITY                       461
INITIAL      XH5,1400       START WITH FIRST GENERATOR                    462
INITIAL      XH12,1         START WITH FIRST GENERATOR                    463
INITIAL      XH4,500        START WITH FIRST AREA                         464
12 FUNCTION  XH12,L6        CORRESPONDING TRIAL WIND INTERCEPT AREA       465
500          450            400         390        380        380         466
CLEAR        XH4-XH99,X398                                                467
START        1              SET TRANSACTION COUNT AND BEGIN SIMULATION    468
-            -              -          -          -          -            -
CLEAR        XH4-XH99,X398                                                489
START        1              SET TRANSACTION COUNT AND BEGIN SIMULATION    490
END                                                                      491
```

Figure 33. Control Cards for Use With Abbreviated
            Simulation Program of Figure 28 in
            Order to Cover the Search Grid of
            Figure 16

of Clear and Start cards. The card numbers match the card numbers of

Figure 28.

VITA

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